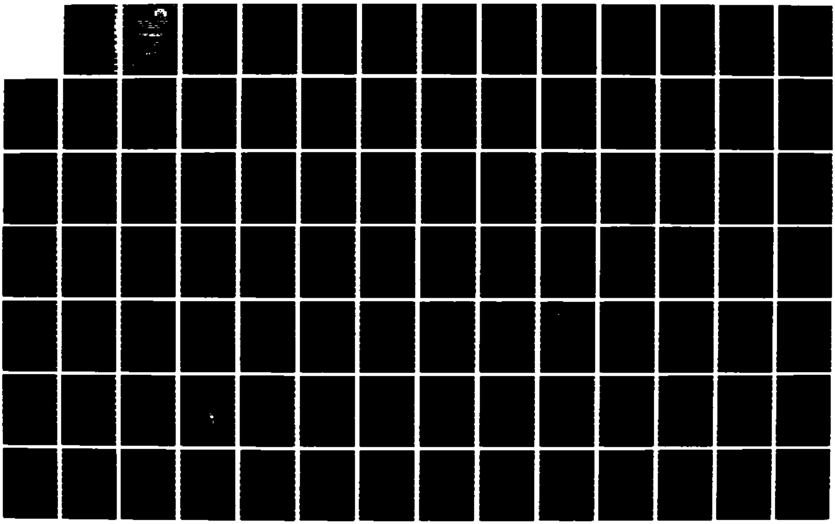
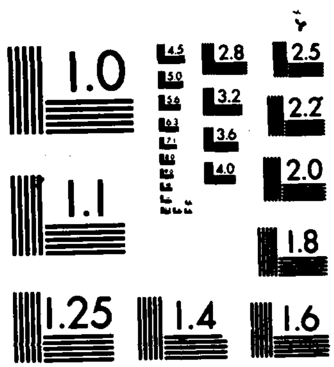
AD-A176 720 THE CORRELATION BETWEEN SYSTOLIC BLOOD PRESSURE MEASURED BY RETURN TO FLO (U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH P J MCCAFFREY DEC 86 1/2

UNCLASSIFIED AFIT/CI/NR-87-2T F/G 6/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

THE CORRELATION BETWEEN SYSTOLIC BLOOD PRESSURE MEASURED BY RETURN TO FLOW VERSUS SYSTOLIC BLOOD PRESSURE MEASURED BY ARTERIAL CATHETER IN THE ADULT ANESTHETIZED PATIENT

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University

By
Patricia J. McCaffrey

University of the State of New York
B.S. Nursing

Director: Salvatore A. Ciresi, MSN, CRNAP
Assistant Professor
Department of Nurse Anesthesiology
School of Allied Health Professions

Virginia Commonwealth University
Richmond, Virginia
December, 1986

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/CI/NR 87-2T	2. GOVT ACCESSION NO. AD-A176720	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Correlation Between Systolic Blood Pressure Measured By Return To Flow Versus Systolic Blood Pressure Measured By Arterial Catheter In The Adult Anesthetized Patient		5. TYPE OF REPORT & PERIOD COVERED THESIS/~~DISSERTATION~~
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Patricia J. McCaffrey		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: Virginia Commonwealth Univ		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433-6583		12. REPORT DATE 1986
		13. NUMBER OF PAGES 122
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES APPROVED FOR PUBLIC RELEASE: IAW AFR 190-1		Lynn Wolaver LYNN E. WOLAVER 14JAN87 Dean for Research and Professional Development AFIT/NR
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) ATTACHED		

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Table of Contents

List of Tables

List of Figures

List of Abbreviations

MAP = Mean arterial pressure

m/sec = Meters per second

ml = Milliliter

mmHg = Millimeters of mercury

sys stat = Systolic stat

Abstract

THE CORRELATION BETWEEN SYSTOLIC BLOOD PRESSURE MEASURED BY RETURN TO FLOW VERSUS SYSTOLIC BLOOD PRESSURE MEASURED BY ARTERIAL CATHETER IN THE ADULT ANESTHETIZED PATIENT

Patricia J. McCaffrey

School of Allied Health Professions - Virginia Commonwealth University, 1986

Major Director: Salvatore Ciresi, M.S., CRNAP

The accurate measurement of blood pressure is essential to the conduct of a safe anesthetic. There is a continuing controversy over which means of blood pressure measurement is best in a particular clinical setting. This study examined the clinical usefulness of a new, automated, indirect method of systolic blood pressure measurement using a return to flow technique. The new method of blood pressure determination has the advantage of providing one systolic pressure value every 10 seconds. This represents a significant improvement over the rate of determination currently available by indirect methods.

Patients selected for this study were those whose medical condition or planned procedure required the insertion of an intra-arterial catheter prior to the induction of anesthesia. The blood pressure cuff was placed on the arm opposite the intra-arterial catheter and a photoelectric pulse plethysmograph was placed on a finger distal to the cuff. After the induction of anesthesia, the

researcher activated the sys stat mode of the blood pressure monitor. Blood pressure readings were recorded during a one minute determination cycle; simultaneous readings were taken from the digital display of the intra-arterial catheter. After a determination cycle, the occlusive cuff was deflated for two minutes, and then the blood pressure monitor was recycled in the stat mode for another minute. The researcher repeated this pattern until five sets of data points were obtained.

The results from the new indirect method were compared to simultaneous measurements obtained by an intra-arterial catheter. A total of 653 pairs of blood pressure measurements were obtained from 18 patients. The systolic stat mode of the automatic blood pressure monitor provided a mean of seven systolic pressure readings in a one minute period. The range of reading numbers in a one minute period were from five to ten. The mean value for blood pressure measured by the systolic stat method was 110 mmHg with a standard deviation of 26.58 mmHg. The mean value for systolic blood pressure measured by intra-arterial catheter was 125 mmHg with a standard deviation of 24.71 mmHg. The Pearson correlation coefficient between the pressures measured by the different methods was found to be .76 for all the data ($p < 0.001$). Correlation coefficients for the individual patients ranged from .16 to .97.

Chapter 1

Introduction

Description of the Problem

The monitoring of blood pressure is essential to the conduct of a safe anesthetic (38, 49, 79, 100). There is a continuing controversy about which means of blood pressure measurement is best in a particular clinical setting (85, 92). The clinical factors influencing the choice of a blood pressure monitor include the patient's age, general state of health, type and extent of underlying disease, type of anesthetic planned, and type and extent of surgery planned (49). All these factors are used to determine the required precision and frequency of blood pressure measurement.

Technological advances have made several methods available to measure blood pressure (66, 100). These include the manual blood pressure cuff, the automated blood pressure cuff, and the intra-arterial catheter. Each of these techniques has risks, benefits, and limitations. The primary goal of every technique is a reliable measurement of blood pressure upon which to base treatment (92). The risks and limitations of each of these procedures vary considerably.

The combination of the manual occlusive cuff and sphygmomanometer is one of the oldest means used to determine blood pressure. This procedure is simple, allows for variability of speed, and carries very low risk to the patient (49, 92). Unfortunately, changing the length of the determination cycle often trades speed for accuracy. The anesthetist can choose to deflate the blood pressure cuff at the recommended rate of 2-3 millimeters of mercury per second and devote full attention to listening for the sounds which indicate systolic and diastolic blood pressure (56). This technique is accurate, but time-consuming. If time is limited, the anesthetist can estimate blood pressure quickly by watching for oscillations on the manometer. This routine is quicker, but less accurate (85). Since these techniques use the same equipment, the speed of determination or accuracy can be selected as the circumstances warrant.

Perhaps the greatest limitation to the use of the manual blood pressure cuff during anesthesia is that frequent measurements are required during the peak of the anesthetist's activities. If the patient's blood pressure is low, there are several actions the anesthetist can take.

These actions include adjusting anesthetic gas flows, changing the table position, and administering medication. It is essential for the anesthetist to monitor the effect these actions, therefore he must divert attention away from treatment to measure blood pressure. The automated blood pressure cuff has the advantage of freeing the anesthetist's hands during these busy periods (49, 85, 100).

There are drawbacks to the currently available automated blood pressure machines. Since the machines have one set cycle to determine a blood pressure, they lack the variability of the manual system. Automatic blood pressure monitors can be set to measure pressures as frequently as once every minute. A normal determination cycle can take from 20 to 50 seconds (3). The length of the cycle may be prolonged if the pulse is irregular or slow, or if patient movement causes artifact (3). The maximum time for the machine to determine a pressure is one and a half minutes. While this is not an unreasonable length of time in many circumstances, it can seem like a very long time when the patient's condition is changing rapidly. This prolonged cycle is uncomfortable for conscious patients. It can also interfere with the function of the intravenous lines distal to the occlusive cuff (66). The intravenous line is essential to the anesthetist for the administration of drugs and fluids. Prolonged deflation times combined with frequent measurements have been implicated in venous stasis, arterial insufficiency, and peripheral nerve damage (26, 88). Despite these disadvantages, the automated blood pressure monitor is a valuable tool in anesthesia. A machine capable of providing more frequent measurements, without sacrificing accuracy, would be an improvement over currently available machines.

The current standard for timely, accurate measurement of blood pressure remains the intra-arterial catheter. It provides information on a beat-to-beat basis. The arterial catheter is placed either to allow arterial blood to be drawn for repeated analysis of blood gases or for the measurement of blood pressure (49, 77). Whichever the primary reason for using the arterial catheter, once it is in place it can be used for both pressure and blood gas measurement.

A major drawback of the arterial catheter is the invasive nature of the procedure (38). The risks from an intra-arterial catheter include infection (0% to 0.06%), bruising (12.7% to 40%), and damage to the artery resulting in thrombosis (24.5% to 27.7%) (67, 70, 95, 98). In a study of arterial catheters in 1,000 patients done by Mandel in 1977, there were only two serious complications that required surgical correction (67). In a 1983 study involving 1,699 cardiovascular surgical patients, no incidence of ischemic damage to the hand or forearm occurred. While the benefits from the information obtained must justify exposing the patient to these risks, the risk of serious injury is decreasing.

Technology is now available to noninvasively measure oxygen saturation and end tidal carbon dioxide in the clinical setting (68, 105). These monitors assist the anesthetist in assessing the adequacy of ventilation without the use of the invasive arterial catheter. This has led to a trend toward more noninvasive monitoring.

The other major reason for using an arterial catheter is to monitor blood pressure. Invasive blood pressure measurement is indicated when the patient's condition or the procedure planned may result in rapid and/or extreme changes in blood pressure (49, 77). The anticipated need for vasoactive drugs is another indication for invasive monitoring (49, 77). Examples of these situations include patients in shock, with poor cardiac function, and patients undergoing vascular or intracranial surgery. Until recently there has been no noninvasive blood pressure monitor available that could measure pressure more frequently than once per minute.

To meet the need for more frequent blood pressure determinations several manufacturers have developed machines with dual capabilities. During periods of hemodynamic stability, the oscillometric method of blood pressure measurement is used. During periods of rapid change, the operator may choose a faster mode. The Dinamap™ automatic oscillometric blood pressure monitor has met this need by incorporating a "stat" mode into the monitor that increases the speed of the determination cycle by relaxing the artifact rejection criteria (22).

The Ohmeda™ 2120 automatic oscillometric monitor has met the need for more rapid blood pressure measurement by developing a new mode. This mode utilizes a blood pressure cuff to apply pressure to the artery. Rather than sensing changes in intra-cuff pressure, the machine uses a pulse plethysmograph to detect the pulse distal to the occlusive cuff (75). The pulse plethysmograph detects the increase in volume caused by the arterial pulse. A light source is directed into the tissue and the amount of light absorbed is detected. Since the tissue volume is constant except for the arterial blood flow, the increase in absorbtion of light in the finger represents the arterial pulse.

The mode using the pulse plethysmograph is called the systolic stat mode or "sys stat". Approximately one measurement of systolic pressure is provided every 10 seconds for a one-minute period (75). This represents a compromise between an accurate complete reading of systolic, diastolic and mean pressures, and an accurate rapid determination of systolic pressure only. The sys stat mode should increase the rate at which systolic blood pressure readings are available without a decrease in the adequacy of the readings. Thus, the condition of the patient is monitored and updated rapidly. The validity of the sys stat mode of the Ohmeda™ 2120 automatic blood pressure monitor is the focus of this study.

Significance

Automated blood pressure monitors are now in common use (49). While their accuracy is considered to be clinically useful, they are slower than needed in certain circumstances (66, 77). To overcome this problem, the manufacturers have tried various techniques to increase the speed of their monitors (22, 75). This study was designed to evaluate the clinical usefulness of one new method of rapid blood pressure monitoring. It compares the values obtained by the new sys stat indirect measurement of systolic pressure to the systolic pressure values obtained directly from an arterial catheter.

Research Question

What is the relationship between the systolic blood pressure measured by the automated return to flow (sys stat) method and the systolic blood pressure measured directly by arterial catheter?

Theoretical Framework

This study examined the measurement of blood pressure at two different sites in the vascular system using two different techniques of measurement. The indirect measurement used an occlusive cuff on the upper arm to occlude the artery, and a pulse detector on the finger to detect the pulse. The actual site of measurement is the upper arm (23). In contrast, the direct method used a catheter inserted into the radial artery to measure pressure at that site.

To understand what was measured by the study several areas will be reviewed. These area include the arterial blood pressure, the pressure pulse wave, and the regulation and variability of blood pressure. Also covered will be the characteristic of the two measurement systems.

The Arterial Pressure

The circulatory system provides for the transportation of oxygen and nutrients to the tissues of the body (37).

The major components of the system are the heart and blood vessels (45). The heart pumps approximately 5000 ml of blood each minute into the aorta (37). The blood flows through the arteries to the smaller arterioles and then to the capillaries. The actual exchange of fluid, nutrients, electrolytes, hormones, and other substances takes place in the capillary beds (45). After leaving the capillary bed, the blood returns to the heart by the venous system (45). This discussion will focus only on the arterial system.

Blood pressure within the vascular system is determined by the flow of blood as generated by the cardiac output, hydrostatic pressure, and the total resistance to that flow. The heart provides the energy for the system and this energy travels through the vascular system as a wave. Brunner defines a wave as a "traveling disturbance that carries energy" (14). The characteristics of a wave are frequency, amplitude, and velocity. The steepness, or rate of rise of a wave form, is called the transient of the wave front (14). The pressure pulse generated by the heart moves 15 to 100 times faster than the blood flow itself. Blood flow is directly proportional to the change in pressure and inversely proportional to the resistance to flow. The inter-relationship of these forces is represented by the fluid mechanics equilibrant of Ohm's Law with the mathematical formula (45):

$$Q = \frac{\text{Change } P}{R}$$

Where Q = blood flow

Change P = pressure difference

R = resistance

The systemic arterial system is a high-pressure system. The heart creates an average pressure of 100 millimeters of mercury (mmHg) in the aorta (45). The pumping action of the heart causes the normal pressure to fluctuate from a high (systolic) pressure of 120 mmHg to a low (diastolic) pressure of 80 mmHg. If the pressures in the arterial system are continuously recorded on a moving graph, a wave form is produced (see Figure 1).

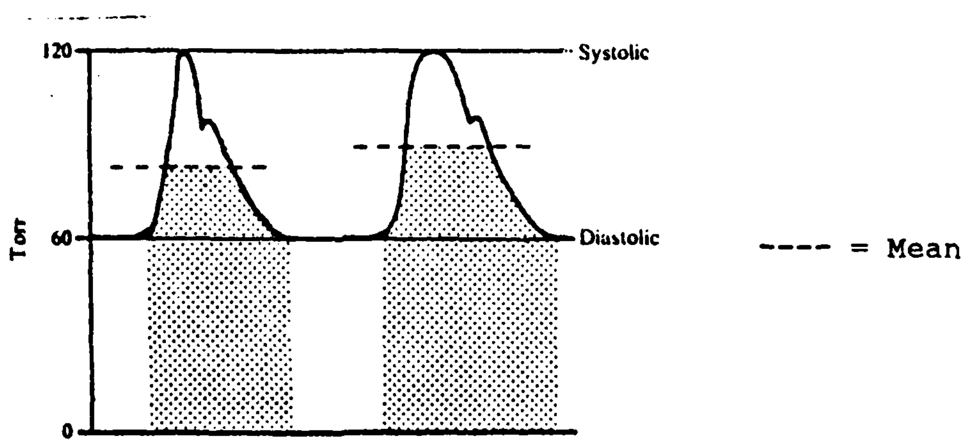


Figure 1. Systolic and diastolic versus mean pressure in mmHg. Note. From Monitoring Practice in Clinical Anesthesia (p. 44) by P. S. Gravenstein, 1982, Philadelphia: J. B. Lippencott.

This wave form is useful in determining not only the absolute value of the different components, but the duration and rate of change as well. In examining the wave form, the initial upstroke, or transient, is steep and represents the velocity of cardiac muscle contraction. This is affected by three factors; preload, afterload, and contractility. The definition of preload is the amount of stretch in the cardiac muscle just prior to contraction (37). An increase in preload results in an increase in the velocity of cardiac contraction (37). Afterload is the amount of energy the heart must use to eject the blood from the ventricle (37). An increase in afterload slows the rate at which the ventricle is able to contract (37). Contractility is the "intrinsic contractile state of the myocardium". An increase results in an increase in the rate of muscle shortening (14).

While the peak pressure in the system is determined mainly by the initial upstroke, the mean pressure is represented by the area under the pressure wave curve. The mean pressure is determined by the height and shape of the wave form (see Figure 1). The shape of the wave is filled in by the actual flow of blood from the ventricle and depends on the amount of blood ejected and the rate of runoff. As long as the rate of volume input exceeds the rate of runoff, the pressure will continue to rise.

At the end of ventricular ejection, the pressure will decrease until the next ventricular contraction. The slope of the pressure wave during diastole depends on the resistance to flow and the length of the diastolic period (14).

Each of the pressures is of concern in different situations. For example, blood flow to the tissue is ensured by the gradient of the mean pressure from the aorta to the tissue (Change P in Ohm's Law). The diastolic pressure is one factor that effects perfusion of the coronary arteries because most flow in these arteries occurs during diastole. The systolic pressure is one determinant of myocardial oxygen demand (81). The difference between the systolic pressure and the diastolic pressure is called the pulse pressure and is an indication of the response of the baroreceptors (81). Each pressure is important in its own way. However, the sys stat mode is only capable of measuring systolic pressure. Therefore, this discussion will focus primarily on the systolic pressure.

The Pressure Pulse Wave

"The systemic arterial pulse is a complex phenomenon," Bruner stated (15). The heart is a pulsatile pump ejecting approximately 85 ml of blood into the aorta with each contraction. While the blood itself will take several heart-beats to reach the periphery, the pulse wave generated will take only 200 - 300 milliseconds to travel the same distance (14). This difference is due to the heart creating both a hydraulic pressure wave which moves at an average speed of 10 meters per second (m/sec), and a slower moving flow wave of the blood itself, with an average speed of 0.5 m/sec (14).

The contour or shape of the pressure wave depends on the stroke volume, ejection rate, and the compliance of the arterial system (36). The stroke volume is the amount of blood ejected with a single heart beat and is measured in milliliters per beat (45). The ejection rate is the speed with which this blood is pumped into the aorta and is measured as the volume ejected over a period of time (41). The stroke volume and the ejection rate reflect the inotropic state of the heart and determine the shape of the pressure wave as it leaves the heart.

Once the pulse wave has left the heart, it is acted on by the capacitance of the arterial system. The capacitance is the change in pressure that occurs with a given change in volume (14). While the stroke volume determines the change in volume presented to the vessels, the underlying elasticity of the vessels and the vasomotor tone within the system determine the change in pressure that occurs with a specific change in volume. These factors can affect the wave after it leaves the heart (15, 45). Figure 2 shows the changes which occur in the pulse pressure as it moves from the aorta to the tissue capillaries and back to the heart. These changes are due to the change in structure and elasticity of the vascular system.

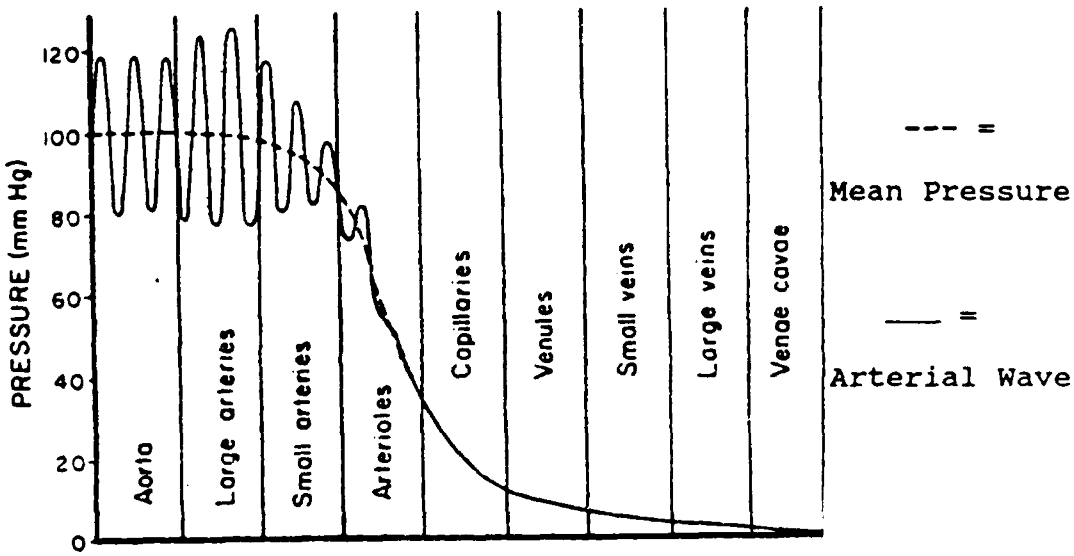


Figure 2. Arterial pressure tracing from aorta to vena cava. Note. From Textbook of Medical Physiology (6th ed.) (p. 238) by A. C. Guyton, 1981, Philadelphia: W. B. Saunders Co.

The structure of the arterial system changes near its distal portion, there is an increase in the number of vessels and a decrease in their size and elasticity (36). Even though the vessels become progressively smaller toward the periphery, the increase in their number results in an increase in the total surface area within the vessels. Impedance is the opposite of capacitance (14). A decrease in capacitance is the same as a increase in impedance (14). The impedance value of the vessel is dependent on the radius of the vessel and the stiffness of the vessel wall. Since the vessels decrease in size and elasticity toward the periphery, there is a gradual increase in the impedance value of the vessel. This results in a gradual increase in peak systolic pressure. Also in the distal vascular system there are areas of abrupt changes in the impedance value of the vessels. These changes, or "mismatches," result in some of the energy of the pulse wave being reflected back toward the central circulation (see Figure 3). This Figure shows the reflected energy being added to the next wave, resulting in an increase in the systolic peak.

Reflected energy is important to the direct measurement of blood pressure because it combines with the forward moving wave, causing a larger systolic wave. This reflection was demonstrated by van Bergan, Weatherhead, Treloar, Dobkin, and Buckley by occluding the brachial artery just distal to the arterial catheter (101). Their results showed a 20-30 mmHg increase in the height of the systolic wave. Since the radial artery is large and located proximal to an area of increased impedance, it is possible that the reflection can increase the systolic pressure as measured by an arterial catheter. While this is recognized as a potential source of error in the use of radial artery catheters, it does not seem to affect the value of the arterial catheter for monitoring trends during anesthesia.

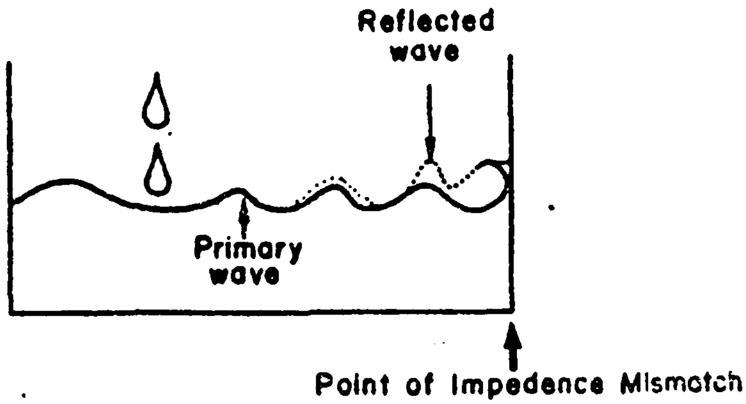


Figure 3. Reflection of the pulse wave.
Note. From "Invasive Blood Pressure Monitoring" by R. F. Bedford in Monitoring in Anesthesia and Critical Care Medicine (p. 52) C. D. Blitt (Ed), 1985, New York: Churchill Livingston.

Regulation of Blood Pressure

The systems used by the body to regulate blood pressure can affect the pressure wave produced and transmitted through the vascular system. These changes can affect the pressure detected by the arterial catheter, and the pulse detected by the plethysmograph. Central regulation of blood pressure maintains adequate perfusion pressure to all the tissues of the body.

Several factors control blood pressure and blood flow (45). These factors include local metabolic needs, sympathetic nervous system stimulation, and hormonal control (86). Control of blood flow to individual tissues is regulated mainly on the basis of local metabolic need. Sympathetic control is used to control perfusion of the body as a whole on a rapid short-term basis. Hormonal control is slower and longer acting.

The body has three major plans for regulating central blood pressure. It can increase total flow by increasing the cardiac output, increasing the total resistance to flow, or moving the fluid volume from the venous system to the arterial system (41). Changes in cardiac output will cause a change in the shape of the arterial pressure wave. Changes in the systolic and diastolic pressure values will depend on how much the flow increases in relation to resistance. The size of the arterioles regulates the amount of resistance in the peripheral circulation. A decrease in the size of these vessels increases the resistance and can decrease blood flow distal to the arteriole. Since the sys stat mode uses a pulse detector located on the finger, the increase in peripheral vascular tone may affect the pulse detected in the finger.

The major sites of resistance to flow are the arterioles. According to Poiseuille's law, "a halving of the radius of a tube will decrease the flow in the tube 16 times" (37). As mentioned previously, flow and resistance are inversely related; an increase in resistance will cause a decrease flow distal to the resistance (14).

The blood flow to the finger can range from a low of 1 milliliter (ml) per 100 grams of tissue per minute to a high of 150 ml per 100 grams per minute (94). The pulse plethysmograph is able to adjust to changes over a wide range of flows. Factors which effect the circulation to the finger during anesthesia include hypothermia, hypotension, and vasoactive drugs. The body's response to decreased temperature in an attempt to prevent further heat loss. The skin is a major source of heat loss, so the body decreases the blood flow to the skin to conserve heat. During periods of hypotension, the body tries to increase the blood pressure by increasing the cardiac output and increasing the resistance. To preserve the central circulation, the increase in resistance (and therefore the decrease in flow) is greatest in the peripheral circulation. Vasoactive drugs effect the size of the blood vessels either directly or by manipulation of the sympathetic nervous system (53).

Variability of Blood Pressure

This study will compare measurements taken simultaneously from different arms because it is impossible to measure blood pressure directly and indirectly simultaneously in the same arm. Any difference in pressures in opposite arms would affect the results of this study. Several previous studies have examined the difference in blood pressure between the two arms. Kristensen and Kornerup compared indirect blood pressure measurements in 197 subjects and found that 49% had differences of 10 millimeters of mercury (mmHg) or more between systolic measurements not taken simultaneously in different arms (58). These were compared to simultaneous indirect measurements, of which only 3.6% on normotensive and 16.1% on hypertensive subjects had a difference of 10 mmHg or more. The authors concluded the variation between arms was usually caused by fluctuations in blood pressure rather than a difference in the pressures in the arms.

A 1960 study by Harrison, Roth, and Hines supported the conclusion. Their study looked at direct, indirect, simultaneous, and non-simultaneous blood pressure measurements. They reported 26.6% of non-simultaneous measurements differed by 10 mmHg or more, while only 5.3% of the simultaneous measurements were 10 mmHg or more apart. These results supported the conclusion that while there may be some variation in blood pressure measured in different arms, the most significant differences are due to the measurements not being taken simultaneously. This study supports the use of opposite arms in the study of the measurement of blood pressure as long as the measurements are taken simultaneously.

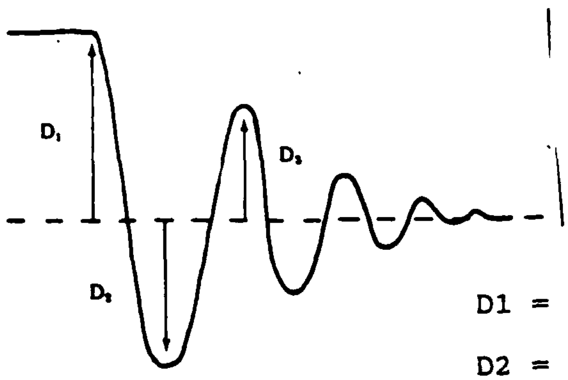
Direct Measurement of Arterial Pressure

The direct measurement of arterial blood pressure involves a cannula in an artery, a system to measure the pressure, and a connection between these two. The most common source of error in this system is believed to be the frequency response of the system (15). The frequency response of a system is its ability to reflect changes in the arterial pulse wave without artificially increasing, decreasing, or changing the shape of the pressure pulse (30). The frequency response needed depends on the frequency of the wave being measured. The two major determinants of frequency response are the amount of damping present and the natural frequency of the system (39). These two characteristics are influenced by the diameter of the catheter, the length of the tubing, the compliance of the tubing, and the presence of bubbles in the fluid path. A smaller diameter and shorter length of the catheter and tubing will lead to greater damping and lower the natural frequency. An increase in the compliance of the tubing will increase the damping and decrease the resonant frequency of the system. The presence of bubbles in the system will have the same effect as increasing the compliance of the tubing. The systems currently available have proved to be clinically reliable. The most common source of error is the presence of air bubbles in the fluid path.

Causes of Error in Direct Measurement

Natural frequency. One source of error in the direct method of blood pressure determination is a measurement system with a natural frequency near the frequency of the pressure being measured. The measurement system itself has a natural frequency and if energy added to the system is close to that frequency, it causes the system to oscillate, or "ring" (39). This is like pushing a child's swing at just the right time to increase the height of the arc. To test the natural frequency of a system, a wave form of known frequency and amplitude is introduced, and the resulting wave form recorded. The system faithfully records the wave form until the frequency approaches the natural frequency. As the natural frequency is approached, the system starts to oscillate and exaggerate the wave form. The definition of the natural frequency of the system is the point of peak oscillation (39). If this frequency is close to that of the arterial pressure wave being measured, this ringing increases the height of the pressure wave, resulting in the systolic pressure being erroneously high.

Damping. Another source of error from the direct measurement of blood pressure is the amount of damping in the measurement system. The ideal level of damping allows the system to respond to changes in pressure without overshooting. Over-damping or under-damping will decrease the accuracy of the system. The amount of damping in the system is expressed as the damping coefficient (39). In a system with no oscillation, the damping coefficient would equal one, and the system would be sluggish in responding to pressure changes (23). If the system permitted oscillation to continue, the damping coefficient would be close to zero and the system would allow oscillations at its natural frequency. The value of the damping coefficient is determined by causing a rapid change in the pressure system and then recording the response. This recording is used to analyze the height of two successive waves (see Figure 4). The amount the height of the second wave decreases from the height of the preceding wave is the basis for determining the damping coefficient.



D1 = Height of first wave

D2 = Height of second wave

D3 = Height of third wave

Figure 4. Damping coefficient determination. Note. From Monitoring Practice in Clinical Anesthesia (p. 76) by P. S. Gravenstein, 1982, Philadelphia: J. B. Lippencott.

To determine the damping coefficient, the height of the second wave squared is divided by the height of the first wave (39). The natural log of this value is divided by the same value plus pi squared (39). The damping coefficient is then determined by taking the square root of the resulting value (39). The following formula is used:

$$\text{damping coefficient} = \sqrt{\frac{\ln D2^2/D1}{\pi^2 + D2^2/D^1}}$$

The same value can be obtained using the graph in Figure 5.

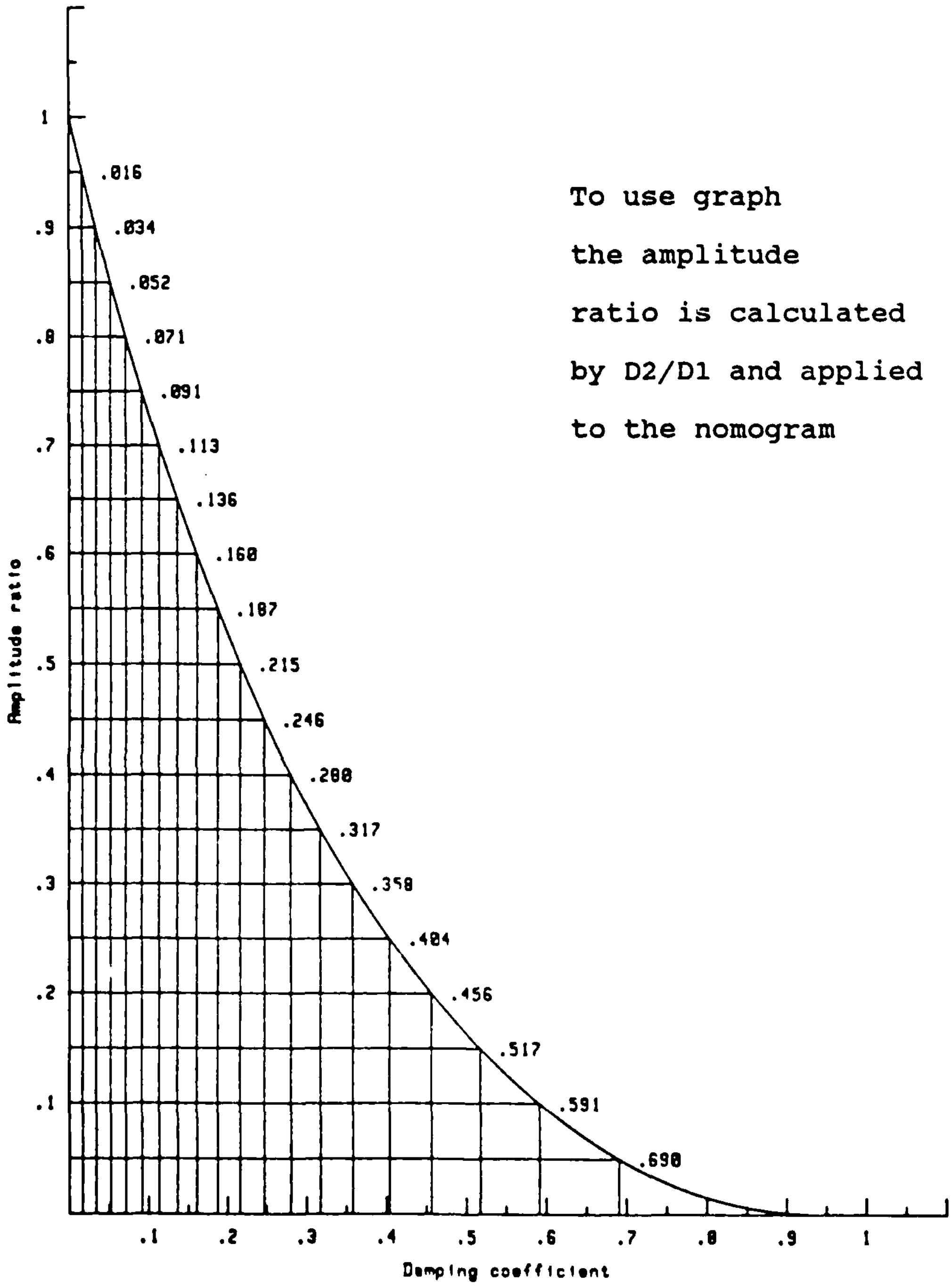


Figure 5. Graph to determine damping coefficient. <u>Note</u>. From <u>Monitoring Practice in Clinical Anesthesia</u> (p. 77) by P. S. Gravenstein, 1982, Philadelphia: J. B. Lippencott.

If the system is overdamped, it will not respond enough to give a true wave form; if it is underdamped, it will over-respond. The arterial system used in this study was tested as a whole to determine its characteristics. It was found to be neither overdamped nor underdamped.

The Blood Pressure Cuff

The size of the blood pressure cuff was one of the first recognized sources of error in blood pressure measurements. The original occlusive cuff used by Riva-Rocci was five centimeters wide. Von Recklinghausen found this size cuff was too narrow and yielded erroneously high readings. While his research established 12 centimeters as the standard cuff width, the optimum width is still in question (90). The American Heart Association has established a minimum size for the width of the occlusive cuff used to determine blood pressure. Since this size varies with the size of the individual whose blood pressure is being taken, they have established a ratio rather than a single size. The ratio is calculated by dividing the width of the occlusive cuff divided by the circumference of the patient's arm; the recommended ratio is 0.4 or greater (10).

The presence of the blood pressure cuff on the arm above the pulse plethysmograph may affect the size and shape of the pulse wave detected by the plethysmograph. The inflation of an occlusive cuff causes the pressure in the artery distal to the occlusive cuff to decrease. London and London found this pressure stabilized at 40-50 mmHg (63). When the occlusive cuff was released, the first sound detected distal to the occlusive cuff preceded the actual blood flow by 0.09 seconds. They described this first pulse under the cuff to be an abrupt, jet-like vertical deflection. In addition, the same researchers found it took longer (0.32 seconds versus 0.17 seconds) for the pulse wave to travel from the heart to a point past the blood pressure cuff than it took to travel the same distance without the cuff. These results imply the first pulse past the blood pressure cuff would have a different configuration than a normal pulse and would take longer to reach the finger. This configuration change may affect the ability of the pulse plethysmograph to accurately detect the pulse. If the plethysmograph is unable to detect the first pulses, the reading will be lower than one determined by the arterial catheter.

The use of an occlusive cuff can increase the venous blood volume in the arm distal to the cuff. This occurs when the pressure in the cuff is less than the arterial systolic pressure but greater than the venous pressure. Blood continues to enter the arm but the cuff prevents blood from returning to the central circulation. The increase in venous volume could affect the pulse plethysmograph's ability to detect a pulse. The sys stat determination cycle requires the occlusive cuff to be inflated from just above the systolic pressure to just below the systolic pressure for a one minute period. This prevents venous drainage from the arm for one minute. Since the arterial flow to the limb is also occluded during most of the period, there should not be significant venous congestion. If the small increase in venous congestion affects the plethysmograph's ability to detect a pulse, the measurements in the one-minute period would become progressively less accurate. To test for this phenomenon, the first blood pressure measurement in each determination set was compared to the last pressure measurement taken at the end of the one-minute cycle.

The Plethysmograph

A plethysmograph is an instrument that measures volume change (51). Measurement of volume change in a limb can give information about blood pressure, heart rate, blood flow, venous flow resistance, and capillary filtration rate (12). The types of plethysmographs available include displacement, strain gauge, impedance, and photoelectric plethysmographs (51). The sys stat mode of the Ohmeda™

2120 blood pressure monitor uses a photoelectric pulse plethysmograph to detect the return of flow in the finger. This discussion will focus on that instrument.

The basis for the photoelectric pulse plethysmograph is the principle that blood absorbs light (83). The photoelectric pulse plethysmograph contains a light source and a photo-detector. These two elements can be mounted either adjacent to, or directly opposite, one another. The energy from the light source is directed into the capillary bed; the photo-detector measures the amount of light reflected back, or transmitted across, the tissue (13, 31). Soft tissue in the body will transmit both visible and infrared radiation. Soft tissue transmits infrared light better than other frequencies of light (20). By using a wave length near infrared, light absorption by the tissue is minimized, permitting the light to penetrate to the deeper vessels of the skin (19). The amount of light the photo-detector senses depends on the amount of blood present to absorb it. The amount of blood in the tissue changes with the pulse wave. The photoelectric pulse plethysmograph will reflect this increase in blood volume as a decrease in the light received by the photodetector (21). Changes in the orientation of the red blood cells during the pressure pulse scatter the light and contribute to the changes in light detected by the photodiode (20). The response of the light detector is nonlinear; therefore the changes caused by the arterial pulse can be detected but not quantified. This an excellent technique to detect the presence of a pulse, but it is impossible to determine blood pressure by the height of the pulse wave form (12, 20). When used on the skin, the photoelectric pulse plethysmograph illuminates at least one cubic centimeter of tissue, and all the vessels in that tissue affect the measurement obtained. Since the same tissue contains both capillary and arteriovenous anastomosis, the pulse reflects total blood flow and not just capillary flow (20).

The photodetector will detect ambient as well as emitted light. Since the changes due to the pressure pulse wave are small, the effect of ambient light can be large. The plethysmograph used in this study controls for ambient light by cycling the light sources in the plethysmograph on and off and taking a reading during these "dark" periods.

The Ohmeda™ 2120 automatic blood pressure monitor uses a photoelectric plethysmograph to detect a pulse distal to the blood pressure cuff. The sys stat mode used in this study is the first monitor to combine a microprocessor-controlled blood pressure cuff and a plethysmograph to rapidly obtain systolic pressures.

Assumptions

1. The pressure was being measured from the same pressure waves in two different arms.

2. The pressure was the same in the brachial and radial artery.

3. The sys stat method of blood pressure measurement was a true reflection of the arterial blood pressure.

Operational Definitions

Allen Test

The Allen test is the traditional test used to determine the adequacy of the arterial flow through the ulnar artery to the hand. It is used to detect arterial insufficiency which may result in ischemia distal to the radial arterial catheter. The patient makes a tight fist and pressure is applied to both the radial and ulnar arteries. The subject is instructed to open the hand and the ulnar artery is released. The test measures the time for the palm of the hand to flush as the blood returns. A normal test is one in which the blood returns in less than 10 seconds (53).

Diastolic Blood Pressure

Diastolic blood pressure is defined as the point of least pressure in the arterial vascular bed (41). The automatic blood pressure device records diastolic blood pressure at the first large decrease in the oscillation amplitude.

Indirect Blood Pressure Measurement

Indirect blood pressure measurement determines the blood pressure at a given point in the system without invading the blood vessel.

Korotkoff Sounds

Korotkoff sounds are rhythmic sounds produced by the intermittent opening of the artery in the limb compressed by the blood pressure cuff as the cuff is deflated from a pressure above systolic to below diastolic pressure (14).

Oscillometric Blood Pressure Measurement

The oscillatory method of blood pressure measurement uses an occlusive cuff technique. Oscillations within the cuff are detected and recorded by a manometer or transducer.

Sys Stat

The sys stat mode of the Ohmeda™ 2120 measures systolic blood pressure by return to flow during an automated one minute cycle.

Systolic Blood Pressure

Systolic blood pressure, defined as the maximum pressure which occurs during contraction of the left ventricle, may be measured directly by the arterial catheter or indirectly by return of flow distal to the blood pressure cuff (41). The automatic blood pressure device records systolic pressure at the first increase in the oscillation amplitude.

Variables

Independent Variable

The independent variable was the method used to determine systolic blood pressure. The pressure was either measured directly at the radial artery with an arterial catheter, or indirectly using an occlusion cuff on the upper arm and a finger plethysmographic pulse detector to detect return of blood flow.

Dependent Variable

The dependent variable was the systolic blood pressure reading obtained.

Limitations

1. The measurements were taken on two different arms.

2. The period of measurement was a period during which changes in blood pressure were expected.

3. The population of patients who required arterial catheters for monitoring during a surgical procedure had more advanced disease states and a higher incidence of peripheral vascular disease than the population as a whole.

Chapter 2

Review of the Literature

This study compared the readings obtained by a new indirect technique of determining systolic arterial blood pressure with values obtained by the direct method of blood pressure determination. To understand these different systems, it is necessary to briefly review the way in which they evolved.

The Direct Arterial Measurement of Blood Pressure

The first description of direct blood pressure measurement was in 1733 by Stephen Hale (9, 30). This English theologian/scientist used a glass tube connected to a brass tube inserted into the artery of a horse to observe that blood rose 8 feet 3 inches up the glass tube. He noted the level of blood in the tube oscillated 2 to 4 inches with the animal's heart beat and respirations (9, 30). Even though Hale had used a U-tube and mercury manometer for other research, he did not use it to measure arterial blood pressure (30). It was almost a century later that a medical student by the name of Poiseuille used the mercury U-tube manometer in the direct measurement of blood pressure in dogs (9, 30). The use of this mercury manometer decreased the size of the measuring apparatus more than 27 times (30).

Carl Ludwig made an important contribution to direct measurement of blood pressure in 1847 when he added a graphic recording device to the mercury manometer. This eliminated observer error and introduced wave forms for analysis (9, 30). Unfortunately, the wave form produced by this apparatus was not a true arterial tracing because of the low frequency response of the mercury manometer system (30).

In the late 1800s, it was recognized the system needed a stiff elastic membrane connected to the pressure source by an incompressable fluid in order to produce an accurate tracing (30). This fluid pathway system used to transmit the pressure is still in use today. It was not used for clinical monitoring until the introduction of open heart surgery in 1953 (80). Two major changes in the system have been the development of catheters to replace of needles (1961) and the use of heparinized continuous flush devices to prevent clotting of blood in the catheter (1969).

Early in the 20th century it was felt that the purely mechanical systems developed produced accurate tracings from which accurate pressures could be quantified. The first systems used the energy of the pressure pulse itself to drive the wave form generator. Later, to increase the quality of the tracing, a system was devised to link the mechanical pressure wave to an optical system which used light and mirrors (30). While these mechano-optical manometers did provide a higher fidelity recording, they also presented some practical difficulties, and were later replaced by electrical systems (30).

The first pressure transducers transformed the mechanical pressure wave coming from the patient into an electrical signal that could be amplified and processed. Since that time, there has been a rapid development of electronic technology employed in pressure transducers and monitors. Currently, pressure transducers, monitors, and wave forms are common in the clinical area.

The Indirect Measurement of Blood Pressure

During the same time that direct means of blood pressure measurement were being developed, the indirect methods were independently evolving. The first attempts involved the placement of weights on a superficial artery until occlusion was noted, but this procedure proved impractical for clinical use. The first blood pressure monitor used clinically was developed in 1876 by von Basch (30). His system used a water-filled bag with a pressure manometer to detect the pressure within the bag. The bag was placed over an artery and the pulse was palpated distally. The pressure was increased by pressing down until the artery was occluded, then the pressure in the bag at that point was noted. This technique, and an air-filled counterpart were found to be clinically useful; providing only a systolic pressure measurement (9).

About the same time, a French physiologist, E.J. Marey, was experimenting with a hydraulic counter-pressure to the forearm. In his work, Marey enclosed the forearm in a chamber, increased the pressure within the chamber, and recorded the oscillations. Marey concluded the point at which oscillations disappeared was the systolic pressure, and the point of maximal oscillation was the diastolic pressure (30). He also noted that, at pressures above systolic, the arm would blanch; the color would return once pressure was reduced below systolic. Observations which provide the basis for current techniques of indirect measurement of blood pressure are: (a) a counter-pressured occludes arterial flow, (b) the manometer indicating counter-pressure showed oscillations, (c) occlusion of the arterial supply causes blanching of the extremity, and (d) color returned when the counter-pressure was reduced below the systolic blood pressure (30). Current methods include palpation, return to flow, oscillometric, and auscultatory. While they all use an occlusive cuff to apply pressure, each uses a different sensor to detect the pulse.

The Development of the Blood Pressure Cuff

The pressure cuff around the extremity to occlude arterial flow is an essential part of all indirect blood pressure measurement. The "blood pressure cuff" was first reported in 1896 by Riva-Rocci. The technique he described involved a rubber bag placed over the brachial artery with a band of nonexpandable material wrapped around the bag. Connected to the bag was a bulb and valve to control inflation and deflation of the cuff. A mercury manometer was used to measure pressure within the bag. Inflation of the bag applied pressure to the tissue under the cuff. When the pressure exceeded the systolic blood pressure, blood flow through the brachial artery ceased (9).

In the Riva-Rocci method, the pressure in the cuff was slowly released while the radial artery was palpated. The systolic pressure was assumed to be the pressure at which the radial pulse returned. Since the cuff width was too narrow, areas of high pressure were created at the edge, leading to an over-estimation of the blood pressure. Von

Rechlingharrsen described this source of error in 1901. The cuff width was changed from the original five centimeters to 12 centimeter and is still in use today. Recently it was recognized that the standard cuff is not suitable for all adults so a wider range of sizes are now available. The American Heart Association has established guidelines which are currently used to determine the correct cuff size (10).

Pulse Detection

Except for the oscillometric method of blood pressure measurement, all other indirect measurement techniques rely on the detection of the pulse distal to the blood pressure cuff. The original routine used by Riva-Rocci involves simple palpation of the arterial pulse. In 1905, a Russian surgeon made a major contribution to blood pressure measurement when he first described the sounds that now bear his name, Korotkoff. N. C. Korotkoff reported that, by placing a stethoscope over the brachial artery at the antecubital fossa, different sounds could be heard at different points in the deflation of the Riva-Rocci cuff from above systolic pressure to zero (32, 81).

Korotkoff concluded that the occlusive cuff blocked the flow of blood in the artery when the pressure in the cuff was greater than the pressure in the artery. The sound generated are from the turbulent flow of blood passing through the partially occluded artery. The first sound detected indicated the systolic pressure and the disappearance of sound was felt to indicate the diastolic pressure. With minor changes this is the technique of blood pressure measurement most widely used today.

The Development of the Oscillometric Method

The cuff developed by Riva-Rocci, when combined with palpation of the arterial pulse, provided a means to measure the systolic blood pressure. It is still used today to obtain systolic pressure on children, in noisy environments, and during periods of hypotension when other methods fail. The major limitation of the method is an inability to obtain mean, diastolic, or pressure pulse values. Shortly after the introduction of the palpatory style of blood pressure determination, it was noted the oscillations of the mercury column were in synchrony with the cardiac cycle. As early as 1897, Hill and Barnard described a modification of the Riva-Rocci procedure (9). The new technique used a sphygmomanometer with a needle pressure gauge to better detect the fluctuations of pressure within the pressure cuff. Hill and Bernard judged the systolic pressure to be where definite oscillations were observed. They felt the diastolic pressure was the point where the oscillations changed from large to small. However, there was no clear agreement on these points until recently (3). This lack of agreement did not interfere with the use of this system in monitoring where trend information was more important than the absolute value. After 1905, the oscillometric method of blood pressure measurement was largely replaced by the auscultatory technique because it provided a reference point for determining both systolic and diastolic pressures (30). Recently, the oscillometric method has been used in some of the automatic blood pressure monitors (79). These machines use a transducer to measure the oscillation of pressure within the cuff and a microprocessor to analyze the amplified signal. The microprocessor used to interpret the signal is sensitive enough to detect changes in the amplitude of the oscillation that the human eye cannot (3). The original machines determined mean arterial pressure (MAP) by detecting the point of maximum oscillations. In a 1979, Ramsey compared the MAP measured by arterial catheter to the MAP measured by the new machine and found a correlation coefficient of .98 (79). With improved technology machines were capable of determining pulse rates, systolic, diastolic, and mean arterial pressures. These machines have gained wide clinical acceptance (66).

Comparison Between Methods

Since there have been more than one method available to measure blood pressure, researchers have compared measurements taken by different means, trying to assess the accuracy of one method compared to another. In 1960, Berliner, Fujiy, Ho Lee, Yildiz, and Garnier conducted a study comparing direct brachial artery pressure measurements to indirect methods using Korotkoff sounds (n = 97). Three sets of readings were taken in the same site of the same arm but not simultaneously. The blood pressure cuff reading was higher than the arterial catheter reading in 61 of the 97 comparisons. They also found 52 of the 97 readings to be within 10 mmHg of one another, while 80 of 97 measurements ranged within 20 mmHg of each other.

Several years later Holland and Humerfelt compared direct pressures from arterial catheters and indirect cuff measurements in 47 patients (48). They found the direct measurement to be higher than the indirect one in readings taken simultaneously in different arms. The correlation coefficient between the two groups was .95 for systolic pressure, and the mean difference between readings was 24.6 mmHg. This showed that, while there was a consistent relation between the pressures determined by the two different techniques, any single reading could have a fairly large error.

The accuracy of a single measurement is much more important in machines used for screening than in machines used for monitoring (4). In 1973, Labarthe, Hawkins, & Remington reached the same conclusion after a study of five different automated blood pressure monitors (60). They compared each of the machines to the auscultatory method of blood pressure measurement and found none accurate enough to be used in blood pressure screening for hypertension. Several years later, the machines had improved to the point where they were considered useful for clinical monitoring. In 1979, Yelderman compared the Dinamap™ and an arterial catheter on 19 patients during coronary artery bypass grafting. The correlation coefficient was .87 with a 95% confidence interval of plus or minus 14 mmHg. The same year, Ramsey conducted a similar study on 28 patients and obtained a correlation coefficient of .92. Part of the improvement in the correlation coefficient that Ramsey obtained could be due to his analyzing the mean of several readings for each patient rather than separate data points.

In a 1981 series of articles, Bruner compared the direct technique of blood pressure determination with several indirect means (15, 16, 17). His results showed a correlation coefficient of .59 for the systolic pressure readings, and .66 for the mean pressure. He stated that the differences in the pressure readings obtained by different techniques were due to the nature of the pressure pulse and the way in which it changed on its way to the periphery. He concluded that the diastolic and mean pressures remained the same, but that the systolic value increased. This increase was due to the reflection of the pressure wave back from the periphery. Since this reflection is greater near the periphery, the difference was greater the further distal the pressure was measured. Finally, he stated that none of the studies to date had really addressed the prcblem of dampening and resonant frequency.

A study by Borrow and Newburger again compared the Dinamap™ to a direct pressure reading (11). The study compared the mean arterial pressure, as read by the automatic blood pressure monitor, to the central arterial pressure. Borrow and Newburger found the correlation coefficient to be .96 for the mean pressures and .86 for the systolic pressures. Hutton and Prys-Roberts repeated Borrows study in 1984. They found a correlation coefficient of .96 for systolic blood pressure and the 95% confidence of a single reading was plus or minus 16.4 mmHg (50). This study was limited in that the readings were not taken simultaneously. More recently, an article by van Egmond, Hasenbos, and Crul compared the simultaneous measurements of direct and indirect blood pressure using an arterial catheter and two different types of automated blood pressure monitors (100). In comparing the systolic pressure readings in the arterial catheter and the oscillometric methods, he found the correlation coefficient to be .36 to .97 for individual patients. From these results, he concluded that the indirect procedure of blood pressure measurement was reasonably accurate. By taking the readings simultaneously, he controlled for any differences in blood pressure that might occur from moment to moment.

The Ohmeda™ 2120 automatic blood pressure monitor is the first automatic blood pressure monitor to combine a microprocessor-controlled blood pressure cuff and a plethysmograph to rapidly obtain systolic pressure measurements. This study compares this new automated method of systolic blood pressure measurement to an established technique, intra-arterial catheterization. No previous study has determined if the new method for systolic readings is accurate and reliable in the clinical setting. Previous studies have shown differences in the readings obtained from direct and indirect means of blood pressure measurement. While it would be better to compare the new indirect method to an already established indirect method there is no other indirect method which could provide frequent readings. The arterial catheter does provide continuous reading, thus it can be used for comparison to the new indirect method (3).

Chapter 3

Methodology

Research Design

The research design of this study was ex-post facto correlational research design. The independent variable was the method of determining systolic blood pressure, either by direct measurement at the radial artery or indirect measurement using an occlusion cuff on the upper arm with a finger plethysmographic pulse detector to detect return of blood flow. The dependent variable was the systolic blood pressure reading obtained.

Data Presentation

The data from this study were analyzed using descriptive statistical analysis, the Pearson product-moment correlation, and estimation of instrument error. The Pearson product-moment correlation coefficient summarizes the magnitude and direction of the relationship between two variables. A coefficient of correlation is a summary of the degree of relationship between the variables. A value of one or negative one represents a perfect positive or negative correlation, and a value of zero represents no relation. This study described the correlation between the values of blood pressure measurement taken simultaneously by two different methods.

The estimation of instrument error was described by Grubbs as a way to quantify the amount of error from each instrument (42). This technique assumes each measurement value obtained is a combination of the "true value" plus instrument or observer error. The variance component was estimated by determining the variance of the sums and differences of the readings from the two instruments.

Description of Sample and Sampling Population

The population consisted of surgical patients at a large southeastern medical center who had an arterial catheter placed preoperatively. The sample excluded patients with impaired circulation to the hand as determined by either history or abnormal Allen test. Also excluded were patients with a history of cardiac arrhythmias.

Procedure

Each participant was seen preoperatively and informed consent was obtained. Blood pressure was determined in each arm using a stethoscope and sphygmomanometer to rule out significant variations between arms. The circumferences of the upper arms were measured to check the blood pressure cuff size applicability. An Allen test was performed on both arms to assess the adequacy of blood flow from both the ulnar and the radial artery. The EKG was checked for arrhythmias.

Prior to beginning data collection, the arterial catheter was calibrated by checking the pressure values on the monitor against a mercury manometer, and the automatic blood pressure cuff was calibrated as specified by the manufacturer.

The blood pressure cuff was placed on the arm opposite the arterial catheter. One pressure reading was obtained using the oscillatory mode of the monitor prior to the start of induction.

After the initial dose of the induction agent had sufficient time to clear the intravenous line tubing and enter the central circulation, the stat mode of the blood pressure monitor was activated. One minute of blood pressure measurements were recorded from the sys stat with the simultaneous readings from the intra-arterial digital display. The occlusive cuff was then deflated for two minutes and then recycled in the stat mode for another minute. This pattern was repeated until five sets of data points were obtained.

Measurement Tools

Oscillometric Blood Pressure Monitor

The machine used was an Ohmeda^{TM} Medical Products 2120 Noninvasive Blood Pressure Monitor. It is a microprocessor-controlled, automated, noninvasive blood pressure monitor which uses the oscillometric method of blood pressure determination. The standard determination cycle consists of the machine inflating the blood pressure cuff to 160 mmHg over a three to six second period. The maximum inflation time is 30 seconds. The machine then deflates the occlusive cuff in a step-wise fashion while the sensitive transducer measures the occlusive cuff pressure and the amplitude of the oscillation within the cuff at each step. This determination cycle is illustrated in the top two channel strips in Figure 6. The top channel shows the pressure being applied to the arm by the occlusive cuff. The middle channel shows the oscillations within the cuff caused by the pulse. The bottom channel is not used in this mode. To control for artifact, the machine looks for two pulsations at each step with relatively equal amplitude (11). At the end of the cycle the pressure cuff deflates completely and the microprocessor analyzes the wave forms and displays the systolic, diastolic, and mean pressure. The deflation sequence can take a maximum of 120 seconds, but normally takes 20 to 50 seconds.

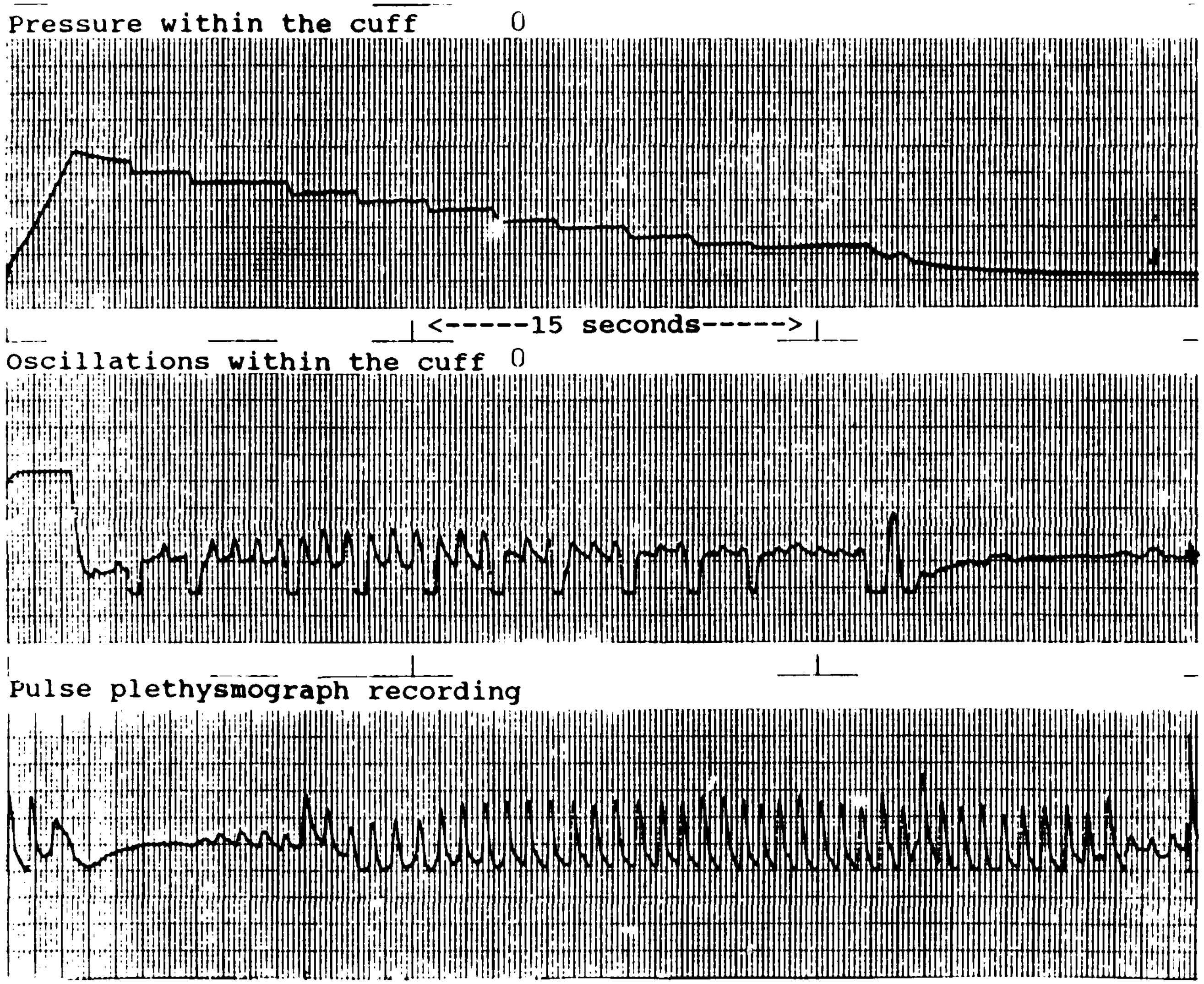


Figure 6. Chart recording of oscillometric automatic blood pressure monitor determination cycle (height of waves not calibrated).

Sys Stat Mode

The stat mode of the machine inflates the blood pressure cuff to suprasystolic pressure, then deflates it until the finger probe senses a pulse in the finger. At that point, rather than continuing deflation, the machine reinflates the cuff to suprasystolic and continuously repeats this cycle for a one-minute period. Each systolic pressure is displayed as it is determined. After the one-minute period, the blood pressure cuff deflates completely. This determination cycle is shown in the top and bottom channel recordings in Figure 7. The top channel strip shows the pressure in the occlusive cuff that is applied to the arm, and the bottom channel reflects the pulse wave detected by the pulse plethysmograph on the finger. The middle channel is not used in this mode.

Pulse Plethysmograph

The finger probe of the sys stat mode is the same probe used for the Ohmeda™ Biox Pulse Oximeter. The probe consists of three components: a light source, a detector, and a heater.

The light source is composed of three light-emitting diodes, one infrared and two red. The two different color light-emitting diodes are used to calculate oxygen saturation of the hemoglobin, a feature not used in this

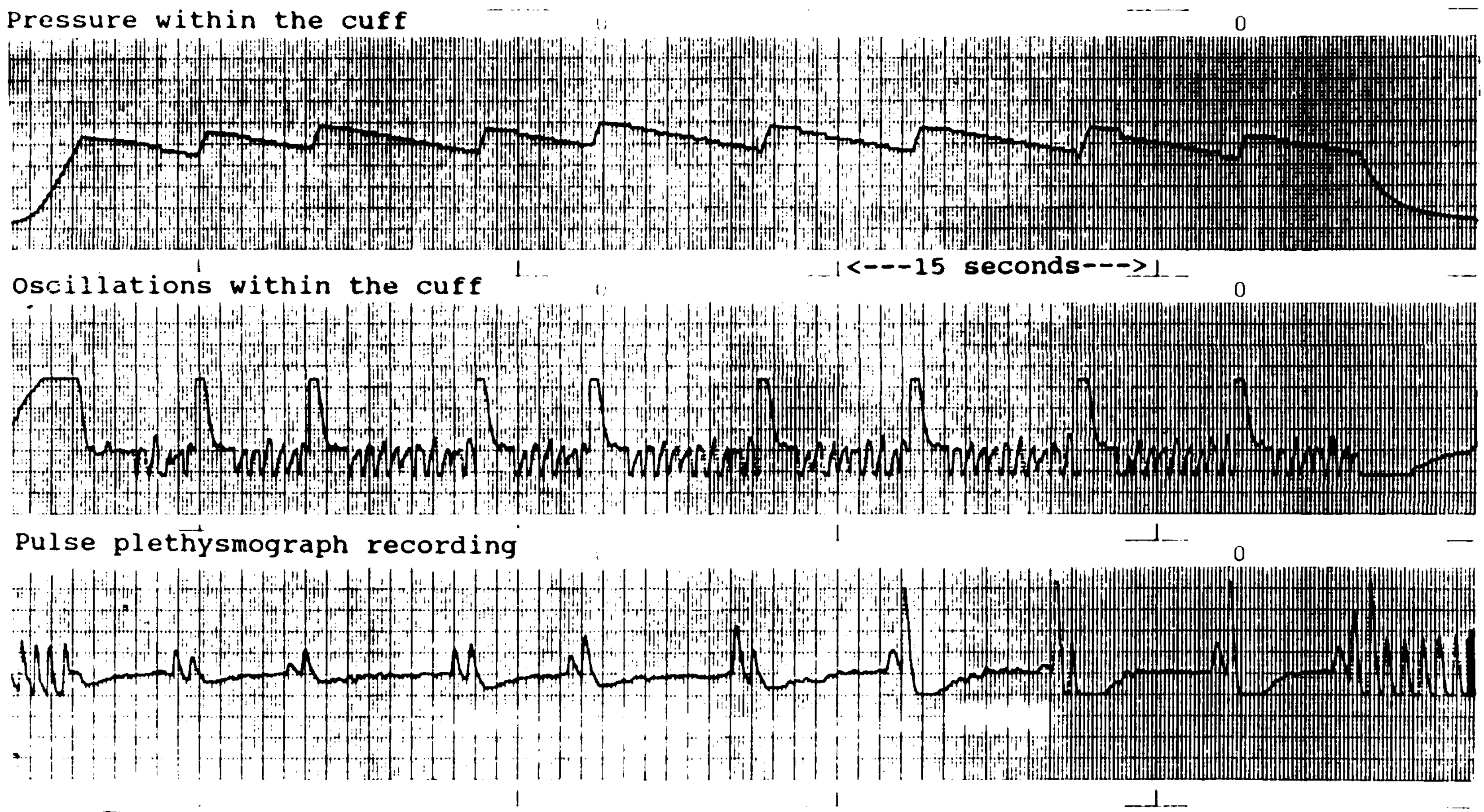


Figure 7. Chart recording of sys stat automatic blood pressure monitor determination cycle (value of waves not calibrated).

study. The detector is a photodiode that produces an electrical current proportional to the light intensity it receives. The heater circuit contains two thermistors which both measure the temperature at the probe site and also thermally stabilize the probe. The light emitting diodes are cycled on and off at 720 cycles per second. The cycling allows the probe to correct for ambient light. The electric current produced by the photodetector is converted to voltage and the analog signal is processed to produce a wave form that represents the pulse wave (75). The microprocessor analyzes this wave form to detect the presence of a pulse in the finger.

Arterial Catheter

The arterial catheter system used in this study to directly measure blood pressure consisted of a catheter, tubing, a pressure transducer, and an electronic monitor. The catheter used was a 20 gauge Angiocath™ or a 20 gauge Arrow™ kit catheter. The transducer was the Trantec™ disposable pressure transducer system produced by American Edwards Laboratories. This system included 210 centimeters of high pressure non-compliant tubing with two three-way stopcocks in line. The sensing portion of the transducer consisted of a microchip imbedded in a silicon gel in contact with the fluid pathway (2). The transducer has an operating range of -50 to +300 mmHg (2). The manufacturer states the accuracy to be within plus or minus 1.5 mmHg from -50 to +60 mmHg and plus or minus 2.5% of the reading from 60 to 300 mmHg (2). The natural frequency of the transducer is 800 hertz nominal (2). The monitor used was the Siemens™ Sirecust 404 pressure monitor which displayed a weighted average for the systolic pressure. All monitors and arterial catheters were tested and calibrated to the manufacturers' specifications before any test procedure in this study.

Chapter 4

Results

A total of 18 patients participated in this study and Table 1 describes the sample. Patient number 3 did not have an arterial catheter placed prior to induction and could not be used in this study. All patients provided informed consent. A total of 670 systolic pressure readings were taken by the return to flow technique and a total of 668 systolic pressure readings were taken by arterial catheter measurement. Two arterial catheter pressure measurements were lost because the line was being flushed at the time the readings should have been taken. There were 15 data pairs with erroneous readings because of patient movement. The erroneous readings constitute 2.25% of the total and were eliminated prior to the data analysis.

Age and Sex

The sample consisted of 9 males and 9 females. The mean age of the group was 58 years, with a range from 40 to 74 years, and a standard deviation of 9.15 years.

Table 1

Description of the Population

Patient number	Age	Sex	Ht cm	Wt lb	Circum Rt	Circum Lt	Cuff/ Arm cir	Allen Lt	Allen Rt	Blood pressure Rt	Blood pressure Lt
1	48	f	150	120	30	29	0.43	2	2	170/90	174/88
2	49	m	175	146	29	28	0.45	2	2	182/100	180/96
4	74	f	163	112	26	25	0.50	3	3	138/74	136/74
5	63	f	163	111	26	25	0.50	4	3	126/94	130/92
6	69	m	180	174	29	28	0.45	3	3	136/74	138/76
7	70	f	140	174	37	36	0.45	3	3	130/78	126/76
8	62	f	157	150	26	26	0.50	3	3	124/80	122/76
9	60	m	173	176	28	28	0.46	3	3	124/86	124/84
10	56	m	168	157	30	29	0.43	4	4	130/90	126/86
11	40	m	178	200	32	31	0.53	4	4	106/60	106/60
12	66	f	168	112	27	27	0.48	3	3	130/70	130/70
13	57	m	185	250	40	39	0.42	2	2	130/80	130/80
14	59	f	163	169	30	30	0.43	3	2	110/70	110/70
15	64	m	165	148	25	27	0.48	4	4	110/70	110/70
16	50	m	165	150	31	31	0.42	4	4	130/70	130/70
17	46	f	160	115	26	26	0.50	2	2	150/90	148/90
18	63	f	163	286	43	42	0.46	4	4	117/66	120/70
19	54	m	178	155	30	32	0.40	5	5	150/80	150/80
Mean	58		166	161	30	30	0.46	3	3		
Minimum	40	f=9	140	111	26	25	0.40	2	2		
Maximum	74	m=9	185	286	43	42	0.53	5	5		
Standard Deviation	9.15		11.03	46.95	4.90	4.73	0.04	0.88	0.90		

Note. Ht = height; Wt = weight; Lt = left; Circum = circumference; Lb = pounds; cm = centimeters; Rt = right; Allen = Allen test in seconds; Cuff/ arm cir = Cuff width to arm circumference ratio

Blood Pressure Cuff to Arm Circumference Ratio

The blood pressure cuff to arm circumference ratio represents the width of the blood pressure cuff used on the patient divided by the circumference of the patient's arm. This value must be greater than 0.40 to meet the American Heart Association's recommendations for blood pressure cuffs and to prevent an erroneously high reading. The mean ratio for this study was 0.46, with a range from 0.40 to 0.53, and a standard deviation of 0.04.

Number of Readings in Each Data Set

The number of sys stat readings in each one minute data set period averaged 7.55, with a range of five to ten readings per minute, and a standard deviation of 1.51.

Arterial Catheter Systolic Pressure

After the erroneous readings were eliminated, 653 observations of arterial catheter systolic blood pressure remained. The readings ranged from 73 mmHg to 199 mmHg (see Table 2). The mean blood pressure reading was 125 mmHg and the standard deviation was 25 mmHg.

Sys Stat Systolic Pressure

After the erroneous data were eliminated,there were 655 observations of sys stat systolic blood pressure

Table 2

Number of Readings, Mean, Standard Deviation, Minimum, Maximum and Pearson Product-Moment for Each Subject and for Total Group

Patient number and measurement source	Number of readings	Mean pressure (mmHg)	Standard deviation (mmHg)	Minimum pressure (mmHg)	Maximum pressure (mmHg)	Correlation coefficient (r =)
1 Arterial	41	129	8.39	111	146	r = .16
1 Sys stat	41	95	11.38	76	124	
2 Arterial	29	138	22.25	112	179	r = .45
2 Sys stat	29	142	30.43	103	240	
4 Arterial	30	111	13.91	96	144	r = .87
4 Sys stat	30	100	22.12	66	152	
5 Arterial	37	140	36.54	87	199	r = .97
5 Sys stat	39	142	37.13	102	205	
6 Arterial	35	105	19.83	78	132	r = .85
6 Sys stat	35	116	19.45	88	156	
7 Arterial	37	149	29.54	96	192	r = .93
7 Sys stat	37	119	28.46	74	164	
8 Arterial	40	118	25.43	82	165	r = .97
8 Sys stat	40	94	23.35	65	139	
9 Arterial	44	116	5.52	107	132	r = .59
9 Sys stat	44	94	6.86	80	109	
10 Arterial	41	134	27.15	97	177	r = .96
10 Sys stat	41	120	24.92	72	156	
11 Arterial	27	104	11.20	79	128	r = .83
11 Sys stat	27	96	12.44	75	130	
12 Arterial	43	100	9.65	86	117	r = .95
12 Sys stat	43	93	10.08	77	111	
13 Arterial	38	129	13.02	107	151	r = .49
13 Sys stat	38	121	11.62	101	140	
14 Arterial	34	97	12.84	73	120	r = .89
14 Sys stat	34	85	10.96	62	99	
15 Arterial	35	136	8.23	118	147	r = .33
15 Sys stat	35	127	30.83	98	216	
16 Arterial	35	124	20.78	91	173	r = .64
16 Sys stat	35	108	20.92	70	152	
17 Arterial	38	135	22.48	101	173	r = .96
17 Sys stat	38	114	23.84	76	156	
18 Arterial	31	153	11.24	135	175	r = .72
18 Sys stat	31	113	13.10	90	145	
19 Arterial	38	131	13.75	115	160	r = .89
19 Sys stat	38	116	20.24	84	181	
All Arterial	653	125	24.71	73	199	
All Sys stat	655	110	26.58	62	240	r = .76

remained. The readings ranged from 62 mmHg to 240 mmHg (see Table 2). The mean blood pressure reading was 110 mmHg and the standard deviation was 27 mmHg.

Arterial Catheter Versus Sys Stat Blood Pressure Measurements

The Pearson product-moment correlation coefficient for individual patients ranged from .16 to .97. A graph and scatterplot of pressure measurements was constructed for each individual patient (see Appendix A).

The correlation coefficient was .76 for the entire population (see Table 2). This correlation ($r=.76$) between systolic blood pressure measurements was considered significant ($p<0.001$). A scatterplot was constructed which indicated a positive correlation about the line of identity (see Figure 8).

The mean value of each group was compared and the mean pressure from the arterial catheter was found to be 15 mmHg higher than the mean pressure from the sys stat mode, which indicates that the values from the arterial catheter were consistently lower than the values from the sys stat mode.

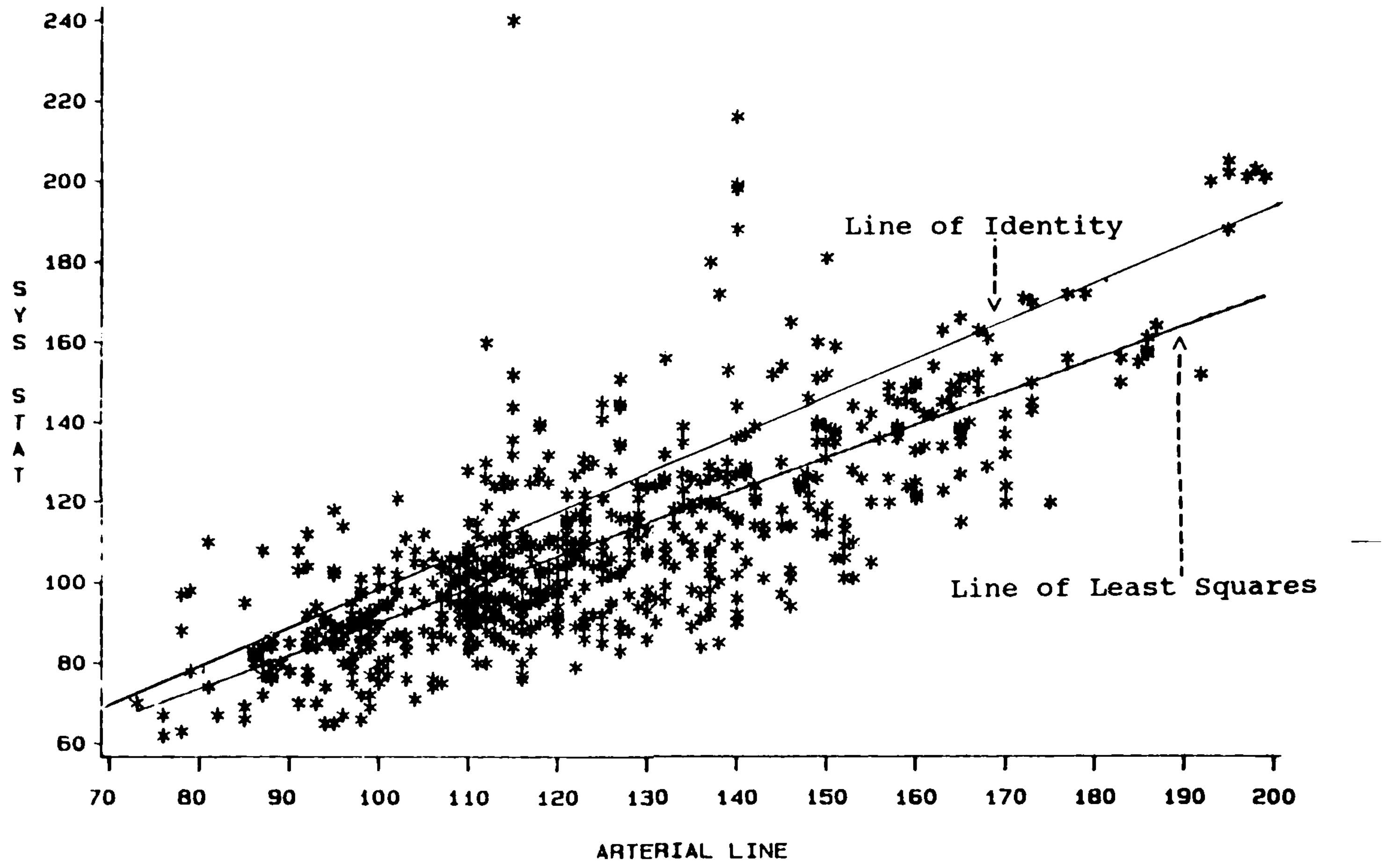


Figure 8. Scatterplot: sys stat vs. arterial catheter for all patients (all values in millimeters of mercury).

The data were also compared using the estimation of instrument error. The standard error of measurement was 15 millimeters of mercury for the sys stat mode and 10 millimeters of mercury for the arterial catheter. These values were then used to calculate the 95% confidence limit for each of the measurement techniques. The 95% confidence limit for the arterial catheter was plus or minus 20 millimeters of mercury, as compared to a 95% confidence limit for the sys stat mode of plus or minus 29 millimeters of mercury (see Table 3).

Table 3

Estimation of Instrument Error in Recording Systolic Pressure by Arterial Catheter and Sys Stat Mode

	Arterial catheter	Sys stat
Minimum	73	62
Maximum	199	240
Mean	125	111
Standard deviation	25	27
Variance	612	719
Standard Error	10	15
95% confidence	20	29

Note. All values in millimeters of mercury

First Measurement Versus Last Measurement

The question of whether venous congestion caused a decrease in the accuracy of the sys stat mode was evaluated by comparing the correlation coefficients for two different data groups (see Table 4). The first data group consisted of all measurements that were made first in the sys stat determination cycle and represent the period of least venous congestion in the finger under the probe. The second data group consisted of all measurements that were made last in a determination cycle and represent the period when venous congestion was greatest. While the correlation coefficient was less for the last group than for the first group (.66 versus .78) the difference did not seem large enough to be problematic.

Table 4

Mean, Standard Deviation, and Pearson Product-Moment for First and Last Pressure Measurements in a Set

	Number of Readings	Mean (mmHg)	Standard Deviation (mmHg)	Minimum reading (mmHg)	Maximum reading (mmHg)	Correlation coefficient
First						
Arterial line	87	124	24.57	76	187	
Sys stat	87	112	24.70	66	188	r=.78
Last						
Arterial line	87	123	24.19	73	199	
Sys stat	87	109	27.68	65	240	r=.66

Chapter 5

Discussion

Conclusions

This study was undertaken to assess the clinical usefulness of a new automated method of indirect blood pressure measurement. While the technique does provide frequent measurements, the accuracy has not been proven to be high enough to be considered reliable. This method does have potential to be reliable and clinically useful but requires further development and evaluation to achieve and validate this goal.

This technique is advantageous because it can provide measurements more frequently than currently available machines. The manufacturer of the machine stated the sys stat mode would provide one measurement every ten seconds. This study found the sys stat mode provided five to ten measurements per minute, compared to one per minute in the oscillometric mode. This is a five to ten fold improvement over currently available methods and would be useful during periods of rapid blood pressure change. The best example of the machine's ability to follow rapid changes in pressure is demonstrated in the last set of measurements on patient number six (see Figure 9). In this measurement set, the sys stat mode closely followed rapid changes in blood pressure. Although the machine provided an improved number of measurements, the correlation coefficient was lower than expected.

The overall correlation coefficient of .76 that resulted from this study was a statistically significant correlation between blood pressures measured by the sys stat mode of the automatic blood pressure cuff and by the arterial catheter. The correlation was not as strong as reported in some previous studies (11, 48, 50, 80, 100, 105). The most frequent statistical test used to compare blood pressure determination techniques is the Pearson correlation coefficient. Previous studies mentioned in the review of literature have found correlation coefficients from .36 to .99 with the majority greater than .80.

The correlation coefficient determined by this study may have been less than those from previous studies for several reasons. The majority of the previous studies took measurements during periods when blood pressure was stable (8, 11, 17, 50, 52, 62, 71, 100). In contrast, this study was done in a clinical setting at times when changes were

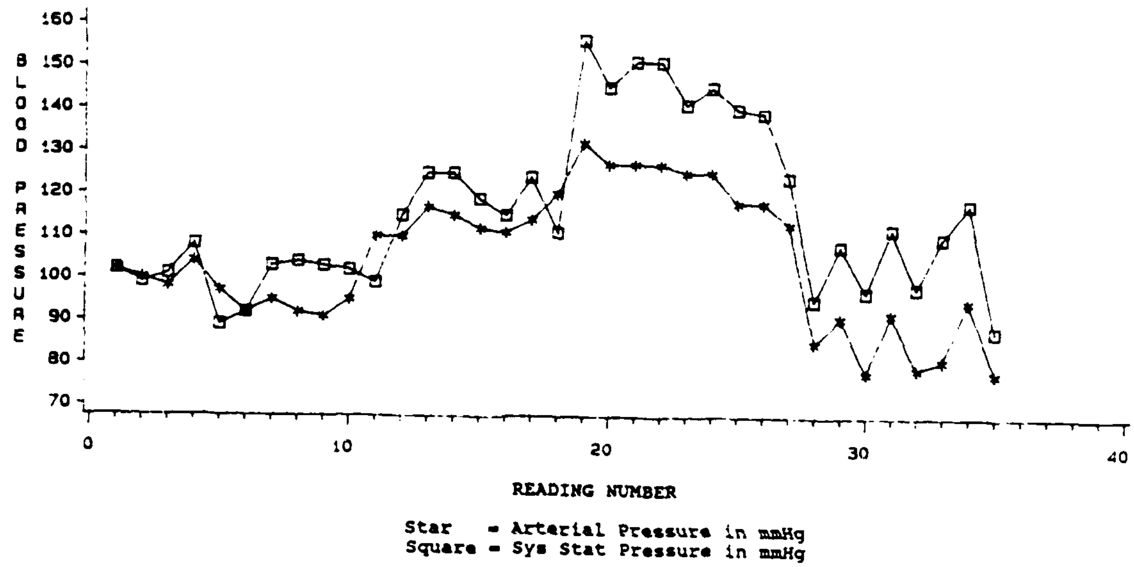


Figure 9. Descriptive statistics: sys stat versus arterial catheter for patient 6.

expected. The measurement period included the induction of anesthesia, laryngoscopy, intubation, positioning, and the surgical scrub of the patient's skin, all of which can affect the patient's blood pressure.

Previous studies also took several measurements with each technique and then compared the mean value of these sets of measurements (8, 11, 48, 79, 106). The data this study used for analysis included the individual data points rather than a mean value of several readings. While this gave a more realistic estimate of how the machine behaved in the clinical setting, it may have resulted in a smaller correlation coefficient than would have been possible under more stable conditions.

It is possible that an increase in the vascular tone in the peripheral circulation affected the pulse detected by the sys stat mode. In examining the graphic records of blood pressure measurements, the peak detected in the sys stat pressure on patient number two and number fifteen indicated the pulse may have been difficult to detect. The fact that the readings became progressively higher indicates the pulse may have been increasingly difficult to find during the one-minute cycle. This could be due either to a decrease in blood flow to the finger or a malfunction of the gain control in the sensing circuit. There were several other periods between measurement cycles when the machine failed to sense a pulse. This problem was corrected by turning the machine off and back on, effectively resetting the gain control. Resetting the gain control resulted in the reacquisition of pulse detection. Therefore, the problem was most probably caused by the gain control, rather than a lack of flow beneath the sensor.

The data from this study were also analyzed by the procedure described by Grubbs to estimate the amount of instrument error (42). This technique has been used in several previous studies, and results in a quantification of the error of each of the methods. When the data were analyzed by this method, the arterial catheter was found to have a smaller standard error than the sys stat mode. The 95% confidence limit was found to be narrower for the arterial catheter than for the sys stat mode (see Table 3). When compared to previous studies, this 95% confidence limit was wider than reported by van Edmond (100).

While the readings were taken simultaneously from the two monitors, there was some difference in the actual pulse wave from which the values were obtained. The procedure involved watching the arterial catheter digital display while the sys stat mode determined a pressure. When the sys stat mode had made a determination, the machine could be heard to recycle. The pressure displayed at the time the sys stat machine recycled was the value recorded as the arterial catheter pressure. This point was used because it most closely represented the actual pulses the sys stat mode had used to determine its pressure value. The arterial catheter monitor displayed a weighted average of several pulse pressures. This system gives a reliable reading of blood pressure without changing the value with each heart beat. In contrast, the value obtained from the sys stat mode is based on the two beats just prior to recycling without the weighted average. As a result of the weighted average formula, the number on the digital display for the arterial catheter is derived from more than the last two beats. The sys stat is based on only those last two beats.

Examination of the raw data and the scatterplot of the readings indicated that the sys stat mode determinations were generally lower than those from the arterial catheter. This relationship was reflected by the line of least squares being below the line of identity (see Figure 8). It was also indicated by the mean of the sys stat measurements being below the mean of the arterial catheter readings (see Table 2). This finding was consistent with the conceptual framework for two reasons. First, Bruner stated that the average systolic pressure was 6 mmHg higher in the radial artery than in the brachial artery (16). The pressure measured at the radial artery is expected to be higher than the pressure measured at the brachial artery. Secondly, the most common error in the arterial catheter is a tendency to overestimate systolic pressure, while the return to flow method tends to underestimate systolic pressure.

Reitan and Barash expressed reservations about using the photoelectric pulse plethysmograph for detection of flow due to the delay created by the distal location of the probe (83). There is no way to tell from this study if a delay in detecting the pulse affected the readings obtained. A delay would have resulted in a higher reading. While the sys stat mode did tend to yield lower readings, this should not be a problem in its use for monitoring because the trends are consistent.

Recommendations

The automated return to flow method of rapid determination of systolic pressure is useful and warrants further investigation. The machine used in this study was a prototype and the manufacturer is aware of the problem with the gain control mentioned in the discussion. The sys stat mode is useful during periods of rapid changes in blood pressure, but it must be used with caution. Frequent activation of the mode has the potential to cause ischemic injury distal to the occlusive cuff.

It would be useful in future studies to record the arterial catheter values and the sys stat mode values on a multichannel recorder to assure that the measurement derived from each system comes from the same pressure pulse. The multichannel graphic recording would also be helpful in detecting errors due to movement or other artifact. The arterial pressure recorder could also be used to determine the damping coefficient and natural frequency of the measurement system immediately prior to each determination cycle. This would document that these factors were at optimum levels for all determinations in the study.

Bibliography

Bibliography

1. Alexander, H., Cohen, M.L., & Steinfeld, L. (1977). Criteria in the choice of an occluding cuff for the indirect measurement of blood pressure. Medical and Biological Engineering & Computing, 15, 2-10.

2. American Edwards Laboratories. (1986). American Edwards presents the Trantec™ disposable pressure transducer. Santa Ana, CA: Author.

3. Apple, H. P. (1980). Automatic noninvasive blood pressure monitors: What is available. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, N. T. Smith, & J. Barden (Eds.), Essential noninvasive monitoring in anesthesia (pp. 7-23). New York: Grune & Stratton.

4. Barker, W. F., Hediger, M. L., Katz, S. H., & Bowers, E. J. (1984). Concurrent validity studies of blood pressure instrumentation-The Philadelphia blood pressure project. Hypertension, 6(1), 85-91.

5. Bassein, L., Borghi, C., Costa, F. V., Strocchi, E., Mussi, A., & Ambrosioni, E. (1985). Comparison of two automatic devices and the standard mercury sphygmomanometer in hypertensive patients. Clinical and Experimental Hypertension. Part A, Theory and Practice, A7(2&3), 387-390.

6. Bedford, R. F. (1985). Invasive blood pressure monitoring. In C. D. Blitt (Ed.), Monitoring in anesthesia and critical care medicine (pp. 41-85). New York: Churchill Livingston.

7. Beirman, E. L. (1985). Obesity. In J. B. Wyngarrden & L. H. Smith (Eds.), Textbook of medicine (pp. 1191-1197). Philadelphia: W.B. Saunders Company.

8. Berliner, K., Fujiy, H., Ho Lee, D., Yildiz, M., & Garnier, B. (1960). The accuracy of blood pressure determinations. Cardiologia, 37, 118-128.

9. Booth, J. (1977). A short history of blood pressure measurement. Proceedings of the Royal Society of Medicine, 70, 793-799.

10. Bordley III, J., Conner, C. A. R., Hamilton, W. F., Kerr, W. J., & Wiggers, C. J. (1951). Recommendations for human blood pressure determinations by sphygmomanometers. Circulation, 4, 503-509.

11. Borrow, K. M., & Newburger, J. W. (1982). Noninvasive estimation of central aortic pressure using the oscillometric method for analyzing systemic artery pulsatile blood flow: Comparative study of indirect systolic, diastolic, and mean brachial artery pressure with simultaneous direct ascending aortic pressure measurements. American Heart Journal, 103, 879-886.

12. Brakkee, A. J. M. (1983). Plethysmographic measurement of peripheral circulatory parameters in man. Advances in Cardiovascular Physics, 5(2), 53-66.

13. Brown, B. H., & Smallwood, R. H. (1981). Medical physics and physiological measurement. Boston: Blackwell Scientific Publications.

14. Bruner, J. M. R. (1978). Handbook of blood pressure monitoring. Littleton, MA: PSG Publishing Company.

15. Bruner, J. M. R., Krenis, L. J., Kunsman, J. M., & Sherman, A. P. (1981). Comparison of direct and indirect methods of measuring arterial blood pressure. Medical Instrumentation, 15, 11-21.

16. Bruner, J. M. R., Krenis, L. J., Kunsman, J. M., & Sherman, A. P. (1981). Comparison of direct and indirect methods of measuring arterial blood pressure, part II. Medical Instrumentation, 15, 97-101.

17. Bruner, J. M. R., Krenis, L. J., Kunsman, J. M., & Sherman, A. P. (1981). Comparison of direct and indirect methods of measuring arterial blood pressure, part III. Medical Instrumentation, 15, 182-188.

18. Carroll, K. K., & Latman, N. S. (1984). Evaluation of electronic, digital blood pressure monitors: failure rates and accuracy. Medical Instrumentation, 18, 263-267.

19. Challoner, A. V. (1976). Measurement of cutaneous blood flow by thermal, optical, and radioisotope methods. Clinical blood flow measurement. New York: Year Book Medical Publishers.

20. Challoner, A. V. (1979). Photoelectric plethysmography for estimating cutaneous blood flow. In P. Rolfe (Ed.), Non-invasive physiological measurements: Vol I (pp. 125-151). New York: Academic Press.

21. Challoner, A. V. J., & Ramsay, C. A. (1974). A photoelectric plethysmograph for the measurement of cutaneous blood flow. Physics in Medicine and Biology, 19, 317-328.

22. Critikon. (1985). Dinamap[TM] adult/pediatric and neonatal vital signs monitor model 1846 operation manual. Tampa, FL: Author.

23. Crul, J. F. (1962). Measurement of Arterial Pressure. Acta Anaesthesiologica Scandinavica, 11, 135-169.

24. Dorlas, J. C., Nijboer, J. A., Butijn, W. T., van der Hoeven, M. A., Settels, J. J., & Wesseling, K. H. (1985). Effects of peripheral vasoconstriction on blood pressure in the finger, measured continuously by a new noninvasive method: The Finapres. Anesthesiology, 62, 342-345.

25. Drips, R. D., Eckenhoff, J. E., & Vandam, L. D. (1982). Introduction to anesthesia: The principles of safe practice (6th ed.). Philadelphia: W. B. Saunders Company.

26. Fink, B. R. (1970). Indirect monitor of blood pressure. Anesthesia and Analgesia, 49, 204-210.

27. Finnie, K. J. C., Watts, D. G., & Armstrong, P. W. (1984). Biases in the measurement of arterial pressure. Critical Care Medicine, 12, 965-968.

28. Fry, D. L. (1960). Physiologic recording by modern instruments with particular reference to pressure recording. Physiological Reviews, 40, 753-788.

29. Gardner, R. M. (1981). Direct blood pressure measurement--Dynamic response requirements. Anesthesiology, 54, 227-236.

30. Geddes, L. A. (1970). The direct and indirect measurement of blood pressure. Chicago: Year Book Publishers.

31. Geddes, L. A., & Baker, L. E. (1968). Principles of applied biomedical instrumentation. New York: John Wiley and Sons.

32. Geddes, L. A., Hoff, H. E., & Badger, A. S. (1966). Introduction of the auscultatory method of measuring blood pressure--including a translation of Korotkoff's original paper. Cardiovascular Research Center Bulletin, 5, 57-74.

33. Geddes, L. A., & Moore, A. G. (1968). The efficient detection of Korotkoff sounds. Medical & Biological Engineering, 6, 603-609.

34. Geddes, L. A., Voelz, M., Combs, C., Reiner, D., & Babbs, C. F. (1982). Characterization of the oscillometric method for measuring indirect blood pressure. Annals of Biomedical Engineering, 10, 271-280.

35. Geddes, L. A., & Whistler, S. J. (1978). The error in indirect blood pressure measurement with the incorrect size of cuff. American Heart Journal, 96, 4-8.

36. Goethals, M., & Brutsaert, D. L. (1981). On the genesis and propagation of pressure and flow pulses in the mammalian circulation. In A. H. Jageneau (Ed.), Noninvasive methods on cardiovascular hemodynamics (pp. 449-456). New York: Elsevier/North Holland Biomedical Press.

37. Goudsouzian, N., & Karamanian, A. (1984). Physiology for the anesthesiologist (2nd ed.). Norwalk, CT: Appleton-Century-Crofts.

38. Gravenstein, P. S. (1980). Introduction. In P. S. Gravenstein, R. S. Newbower, A. K. Ream, N. T. Smith, & J. Barden (Eds.), Essential noninvasive monitoring in anesthesia (pp. 1-6). New York: Grune & Stratton.

39. Gravenstein, P. S. (1982). Monitoring practice in clinical anesthesia. Philadelphia: J. B. Lippencott.

40. Greatorex, C. A. (1979). Non-invasive blood pressure measurement. In P. Rolfe (Ed.), Non-invasive physiological measurements: Vol I (pp. 193-211). New York: Academic Press.

41. Green, J. F. (1982). Fundamental cardiovascular and pulmonary physiology: An integrated approach for medicine. Philadelphia: Lea & Febiger.

42. Grubbs, F. E. (1948). On estimating precision of measuring instruments and product variability. Journal of the American Statistical Association, 43, 243-264.

43. Gunderson, J. (1972). Segmental measurements of systolic blood pressure in the extremities including the thumb and great toe. Acta Chirurgica Scandinavica, 426, 1-90.

44. Gunderson, J. (1973). Measurement of systolic blood pressure in all fingers. Danish Medical Bulletin, 20, 129-131.

45. Guyton, A. C. (1986). Textbook of Medical Physiology (7th ed.). Philadelphia: W.B. Saunders Co.

46. Harrison, E. G., Jr., Roth, G. M., & Hines, E. A. (1960). Bilateral indirect and direct arterial pressures. Circulation, 12, 419-436.

47. Hirai, M., Nielsen, S. L., & Lassen, N. A. (1976). Blood pressure measurement of all five fingers by strain gauge plethysmography. Scandinavian Journal of Clinical Laboratory Investigation, 36, 627-632.

48. Holland, W. W., & Humerfelt, S. (1964). Measurement of blood-pressure: Comparison of intra-arterial and cuff values. British Medical Journal, 2, 1241-1243.

49. Hug, C. C. (1986). Monitoring in anesthesia. In R. D. Miller (Ed.), Anesthesia (pp. 411-498). New York: Churchill Livingston.

50. Hutton, P. D., & Prys-Roberts, C. (1984). An assessment of the Dinamap 845. Anaesthesia, 39, 261-267.

51. Hyman, C. and Winsor, T. (1961). History of plethysmography. The Journal of Cardiovascular Surgery, 2, 506-518.

52. Johnson, C. J. H., & Kerr J. H. (1985). Automatic blood pressure monitors. Anaesthesia, 40, 471-478.

53. Kaplan, J. A. (1979). Hemodynamic monitoring. In J. A. Kaplan (Ed.), Cardiac anesthesia (pp. 71-115). New York: Grune & Stratton.

54. Karvonen, M. J., Telivuo, L. J., & Jarvinen, E. J. K. (1964). Sphygmomanometer cuff size and the accuracy of indirect measurement of blood pressure. The American Journal of Cardiology, 13, 688-693.

55. Katona, Z., & Bolvary, G. (1983). Automatic sphygmomanometer. Advances in Cardiovascular Physics, 5, 119-143.

56. Kirkendall, W. M., Feinleib, M., Freis, E. D., & Mark, A. L. (1980). Recommendations for human blood pressure determination by sphygmomanometers. Circulation, 62, 1146A-1155A.

57. Krahenbuhl, B., Nielsen, S. L., & Lassen, N. A. (1977). Closure of digital arteries in high vascular tone states as demonstrated by measurement of systolic blood pressure in the fingers. Scandinavian Journal of Clinical Laboratory Investigation, 37, 71-76.

58. Kristensen, B. O., & Kornerup, H. J. (1982). Which arm to measure the blood pressure? Acta Medica Scandinavica, 670, 69-73.

59. Kroeker, E. J., & Wood, E. H. (1955). Comparison of simultaneously recorded central and peripheral arterial pressure pulses during rest, exercise and tilted position in man. Circulation Research, 3, 623-632.

60. Labarthe, D. R., Hawkins, C. M., & Remington, R. D. (1973). Evaluation of performance of selected devices for measuring blood pressure. The American Journal of Cardiology, 32, 546-553.

61. Lagerwerff, J. M., & Luce, R. S. (1970). Artifact suppression in indirect blood pressure measurements. Aerospace Medicine, 41, 1157-1161.

62. Linden, W., & Zimmermann, B. (1984). Comparative accuracy of two new electronic devices for the noninvasive determination of blood pressure. Biofeedback and Self-Regulation, 9, 229-239.

63. London, S. B., & London, R. E. (1967). Comparison of indirect pressure measurements (Korotkoff) with simultaneous direct brachial artery pressure distal to the cuff. Advances in Internal Medicine, 13, 127-142.

64. Loots, W., & Suy, R. (1981). Comparison of plethysmographic and direct electromagnetic flow measurements in man and animal. In A. H. Jageneau (Ed.), Noninvasive methods on cardiovascular hemodynamics (pp. 475-479). New York: Elsevier/North Holland Biomedical Press.

65. Luskin, R. L., Weinstein, R. A., Nathan, C., Chamberlin, W. H., & Kabins, S. A. (1986). Extended use of disposable pressure transducers. Journal of the American Medical Association, 255, 916-920.

66. Maier, W. R. (1985). Noninvasive blood pressure monitoring. In C. D. Blitt (Ed.), Monitoring in anesthesia and critical care medicine (pp. 29-39). New York: Churchill Livingston.

67. Mandel, M. A., & Dauchot, P. J. (1977). Radial artery cannulation in 1,000 patients: Precautions and complications. The Journal of Hand Surgery, 2, 482-485.

68. May, W. S., Heavner, J. E., McWhorter, D., & Racz, G. (1985). Capnography in the operating room. New York: Raven Press.

69. McDougal, B., & Schwarm, D. (1977). Digital blood pressure monitoring in critical care and dialysis patients. Journal of Laboratory Clinical Medicine, 90, 57-60.

70. Mortensen, J. D. (1967). Clinical sequelae from arterial needle puncture, cannulation, and incision. Circulation, 35, 1118-1123.

71. Nystrom, E., Reid, K. H., Bennett, R., Couture, L., & Edmonds, H. L. (1985). A comparison of two automated indirect arterial blood pressure meters: With recordings from a radial catheter in anesthetized surgical patients. Anesthesiology, 62, 526-530.

72. O'Brien, E., Fitzgerald, D., & O'Malley, K. (1985). Blood pressure measurement: current practice and future trends. British Medical Journal, 290, 729-734.

73. O'Brien, E. T., & O'Malley, K. (1979a). The observer. British Medical Journal, 2, 775-776.

74. O'Brien, E. T., & O'Malley, K. (1979b). Reconciling the controversies: a comment on "the literature". British Medical Journal, 2, 1201-1202.

75. Ohmeda. (1986). Model 2110 adult/pediatric nibp monitor service manual. Madison, WI: Author.

76. Polit, D. F., & Hungler, B. P. (1983). Nursing Research - principles and methods (3rd ed.). Philadelphia: J. B. Lippincott Company.

77. Prys-Roberts, C. (1984). Invasive monitoring of the circulation. In L. J. Saidman & N. Smith (Eds.), Monitoring in anesthesia (pp. 79-116). New York: John Wiley and Son.

78. Ragan, C., & Bordley, J., III. (1941). The accuracy of clinical measurements of arterial blood pressure. Bulletin of John Hopkins Medical Center, 69, 504-528.

79. Ramsey, M., III. (1979). Noninvasive automatic determination of mean arterial pressure. Medical & Biological Engineering & Computing, 17, 11-18.

80. Ramsay, M., III. (1980). Noninvasive blood pressure monitoring methods and validation. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, N. T. Smith, & J. Barden (Eds.), Essential noninvasive monitoring in anesthesia (pp. 37-51). New York: Grune & Stratton.

81. Ream, A. K. (1980). Systolic, diastolic, mean of pulse: Which is the best measurement of arterial pressure? In J. S. Gravenstein, R. S. Newbower, A. K. Ream, N. T. Smith, & J. Barden (Eds.), Essential noninvasive monitoring in anesthesia (pp. 53-74). New York: Grune & Stratton.

82. Reeben, V., & Epler, M. (1983). Indirect continuous measurement of mean arterial pressure. Advances in Cardiovascular Physics, 5, 90-118.

83. Reitan, J. A., & Barash, P. G. (1984). Noninvasive monitoring of the circulation. In L. J. Saidman & N. Smith (Eds.), Monitoring in Anesthesia (pp. 117-191). Boston: Butterworth Publishers.

84. Schraibman, I. G., Mott, D., Naylor, G. P., & Charlesworth, D. (1975). Comparison of impedance and strain gauge plethysmography in the measurement of blood flow in the lower limb. British Journal of Surgery, 62, 909-912.

85. Scott, W. A. C. (1985). Haemodynamic monitoring: measurement of systemic blood pressure. Canadian Anaesthetists' Society Journal, 32, 294-298.

86. Shepherd, J. T. (1964). Regulation of blood flow in human limbs. In H. L. Price & P. J. Cohen (Eds.), Effects of Anesthesia on Circulation (pp. 261-277). Springfield, IL: Charles C. Thomas.

87. Shinozaki, T., Deane, R. S., & Mazuzan, J. E. (1980). The dynamic responses of liquid-filled catheter systems for direct measurements of blood pressure. Anesthesiology, 53, 498-504.

88. Showman, A., & Betts, E. K. (1981). Hazard of automatic noninvasive blood pressure monitoring. Anesthesiology, 55, 717-718.

89. Simmons, E. M., Leader, H., Friedman, S. A., Davis, B., Lee, D., Winsor, T., & Caceres, C. A. (1967). A computer program for the peripheral pulse wave. The American Journal of Cardiology, 19, 827-831.

90. Simpson, J. A., Jamieson, G., Dickhaus, D. W., & Grover, R. F. (1965). Effect of size of cuff bladder on accuracy of measurement of indirect blood pressure. American Heart Journal, 70, 208-215.

91. Slogoff, S., Keats, A. S., & Arlund, C. (1983). On the safety of radial artery cannulation. Anesthesiology, 59, 42-47.

92. Smith, N. T., & Beneken, J. E. W. (1980). An overview of arterial pressure monitoring. In J. S. Gravenstein, R. S. Newbower, A. K. Ream, N. T. Smith, & J. Barden (Eds.), Essential noninvasive monitoring in anesthesia (pp. 75-88). New York: Grune & Stratton.

93. Smith, N. T., Wesseling, K. H., & de Wit, B. (1985). Evaluation of two prototype devices producing noninvasive, pulsatile, calibrated blood pressure measurement from a finger. Journal of Clinical Monitoring, 1, 17-29.

94. Strandness, E. D., & Sumner, D. S. (1975). Hemodynamics for surgeons. New York: Grune & Stratton.

95. Stratton, C. W. (1983). Bacterial infection from intravascular monitoring devices. Infection Control, 4, 399-401.

96. Sy, W. P. (1981). Ulnar nerve palsy possibly related to use of automatically cycled blood pressure cuff. Anesthesia and Analgesia, 60, 687-688.

97. Taylor, B. C., Ellis, D. M., & Drew, J. M. (1986). Quantification and simulation of fluid-filled catheter/transducer systems. Medical Instrumentation, 20, 123-129.

98. Toll, M. O. (1984). Direct blood-pressure measurements: risks, technological evolution and some current problems. Medical & Biological Engineering & Computing, 22, 2-5.

99. Vachtsevanos, G., Kalaitzakis, C., Papamarkos, N., Ziakas, G., Economou, K., & Gemitzis, K. (1984). Correlation study of arterial blood pressure level to the amplitude of the pressure pulse waveform. Journal of Biomedical Engineering, 6, 33-39.

100. van Egmond, J., Hasenbos, M., & Crul, J. F. (1985). Invasive v. noninvasive measurement of arterial pressure. British Journal of Anaesthesia, 57, 434-444.

101. van Bergen, F. H., Weatherhead, D. S., Treloar, A. E., Dobkin, A. B., & Buckley, J. J. (1954). Comparison of indirect and direct methods of measuring arterial blood pressure. Circulation, 10, 481-490.

102. Voors, A. W., Sklov, M. C., Halperin, H., Webber, L. S., & Berenson, G. S. (1982). Comparison of two automatic blood pressure recorders and the mercury sphygmomanometer. Hypertension, 4, 329-336.

103. Weaver, J. C., & Bohr, D. F. (1950). The digital blood pressure. I. Values in normal subjects. American Heart Journal, 39, 413-422.

104. Wheeler, H. B., Pearson, D., O'Connel, D., & Mullick, S. C. (1972). Impedance phlebography - Technique, interpretation, and results. Archives of Surgery, 104, 164-169.

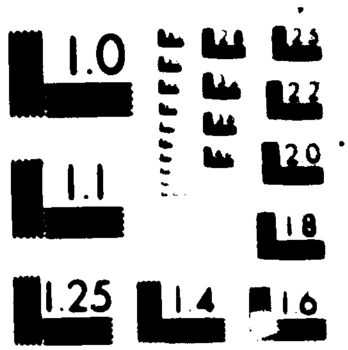
105. Yelderman, M., & New, W. (1983). Evaluation of pulse oximetry. Anesthesiology, 59, 349-352.

106. Yelderman, M. & Ream, A. K. (1979). Indirect measurement of mean blood pressure in the anesthetized patient. Anesthesiology, 50, 253-256.

107. Zezulka, A. V., Sloan, P. J. M., & Beevers, D. G. (1985). Comparison of blood pressure machines. Clinical and Experimental Hypertension. Part A, Theory and Practice, A7, 319-326.

Appendix A

AD-A176 720 THE CORRELATION BETWEEN SYSTOLIC BLOOD PRESSURE 2/2
MEASURED BY RETURN TO FLO (U) AIR FORCE INST OF TECH
WRIGHT-PATTERSON AFB OH P J MCCAFFREY DEC 86
UNCLASSIFIED AFIT/CI/NR-87-2T F/G 6/5 NL


1.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

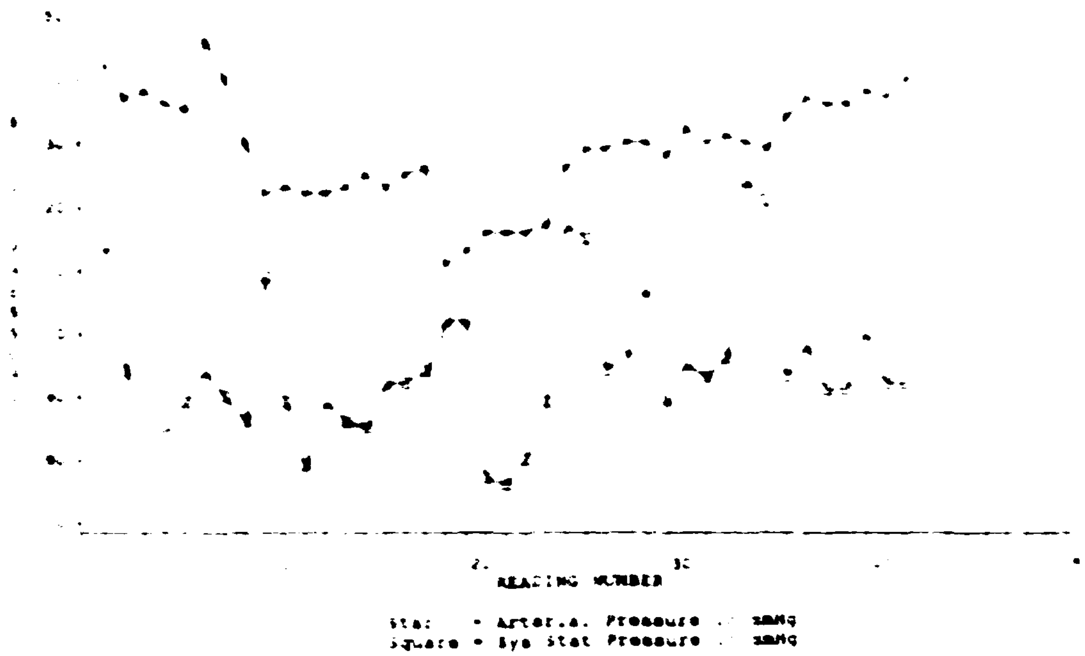


Figure 10. Descriptive statistics: sys stat versus arterial catheter for patient 1.

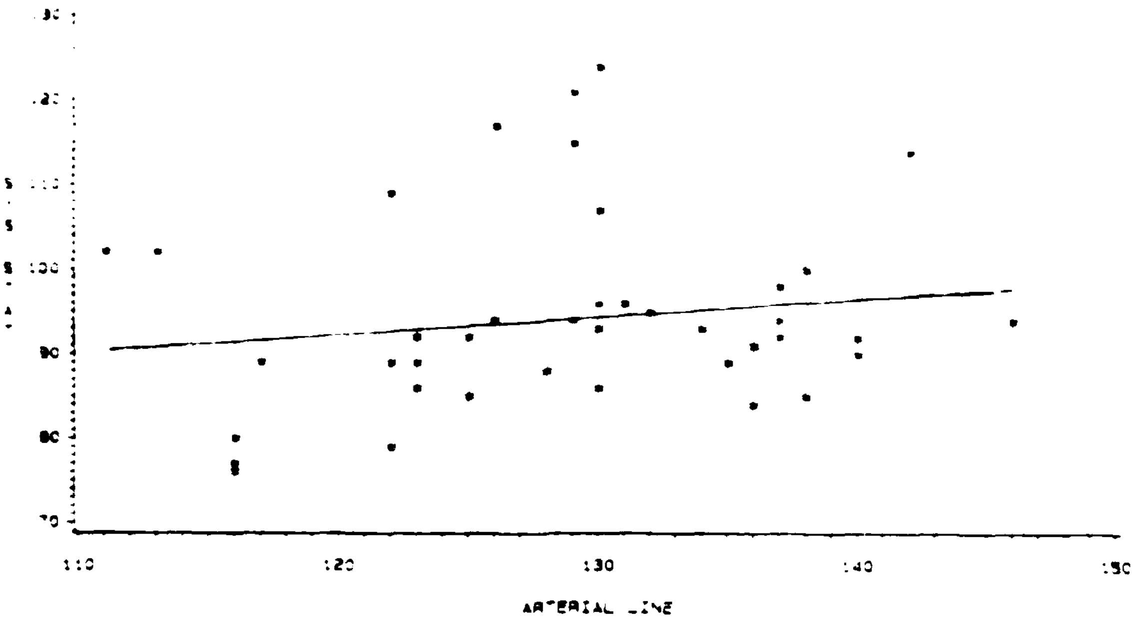


Figure 11. Scatterplot: sys stat versus arterial catheter for patient 1 (all values in mmHg).

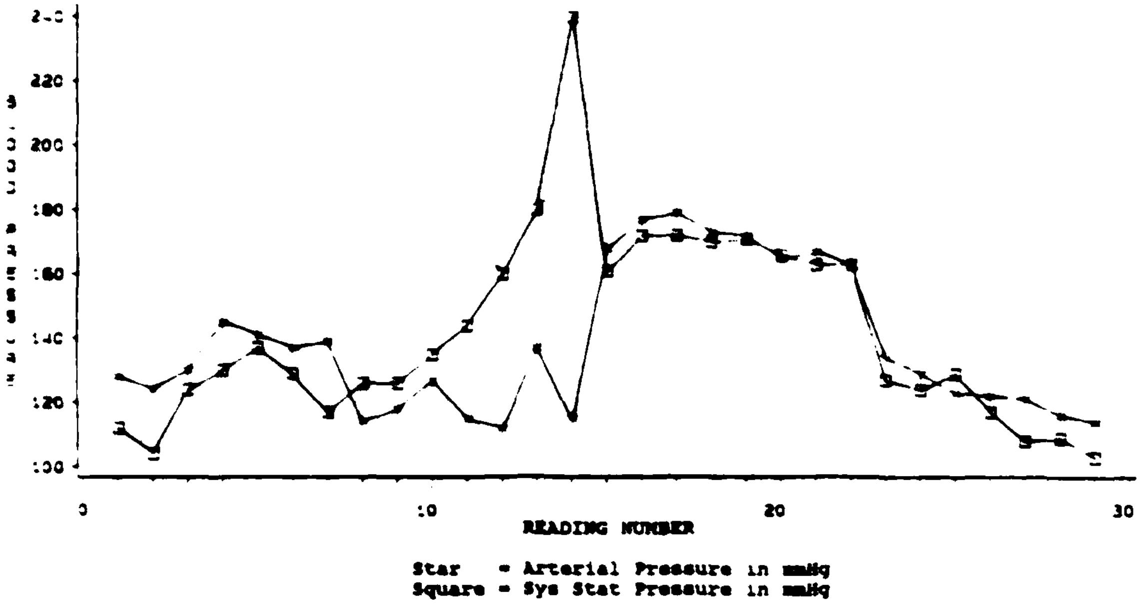


Figure 12. Descriptive statistics: sys stat versus arterial catheter for patient 2.

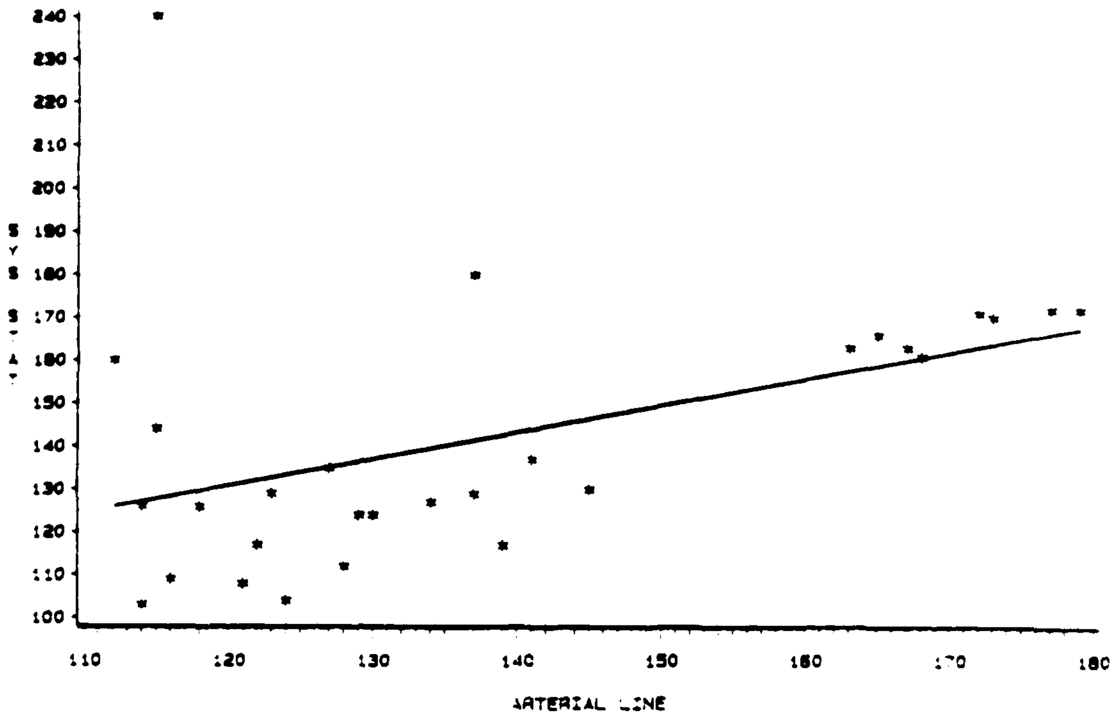


Figure 13. Scatterplot: sys stat versus arterial catheter for patient 2 (All values in mmHg).

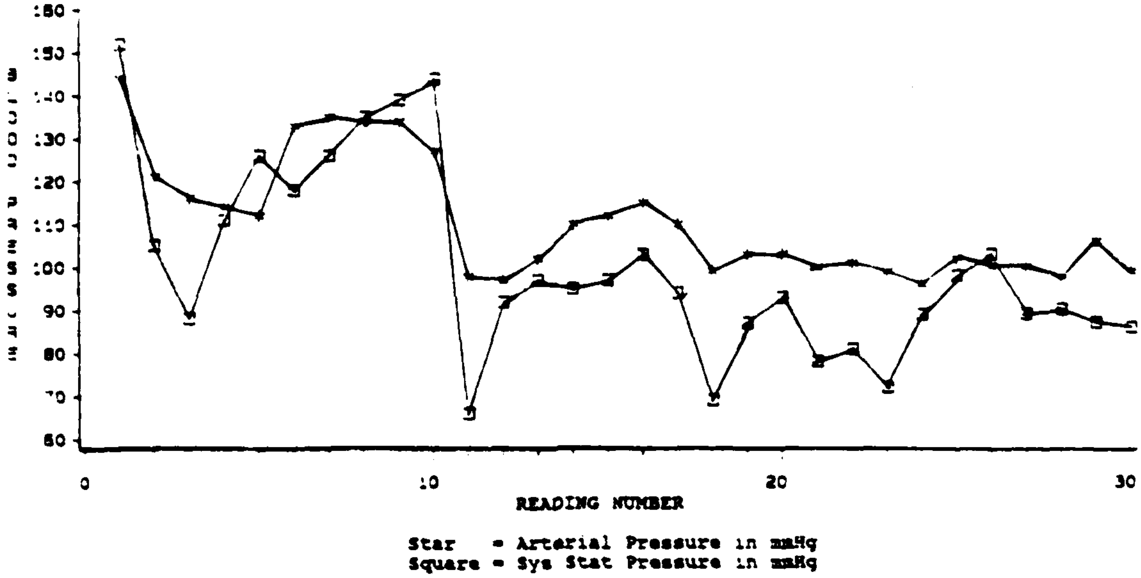


Figure 14. Descriptive statistics: sys stat versus arterial catheter for patient 4.

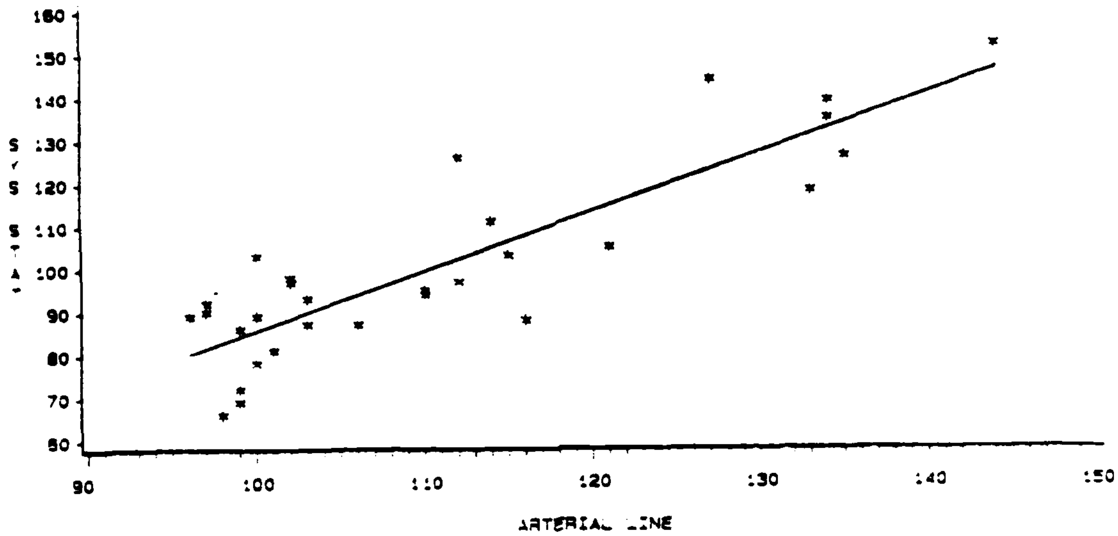


Figure 15. Scatterplot: sys stat versus arterial catheter for patient 4 (All values in mmHg).

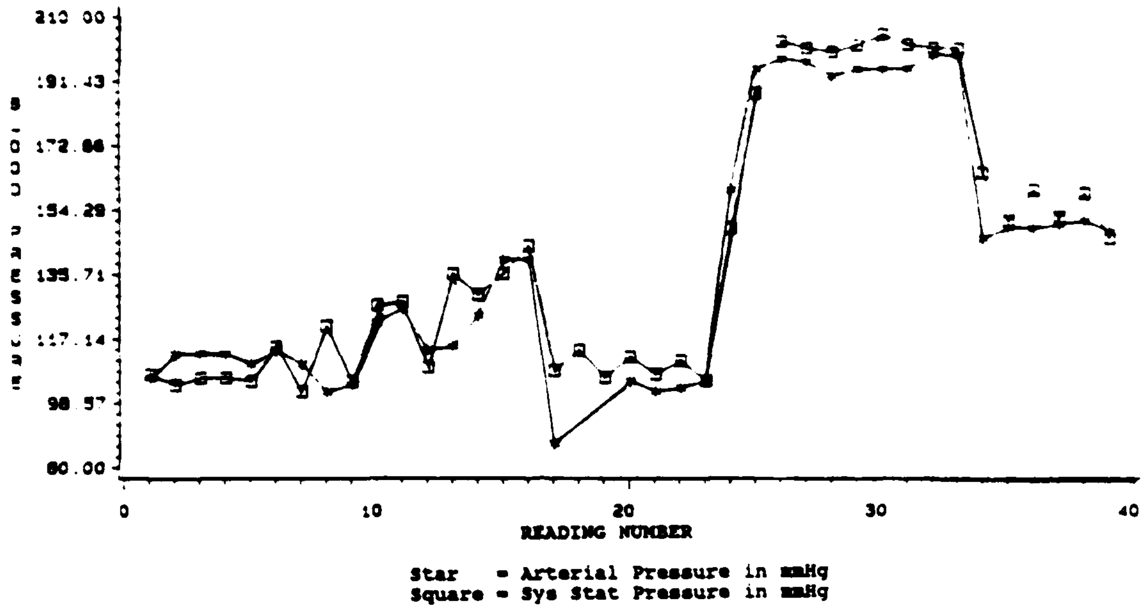


Figure 16. Descriptive statistics: sys stat versus arterial catheter for patient 5.

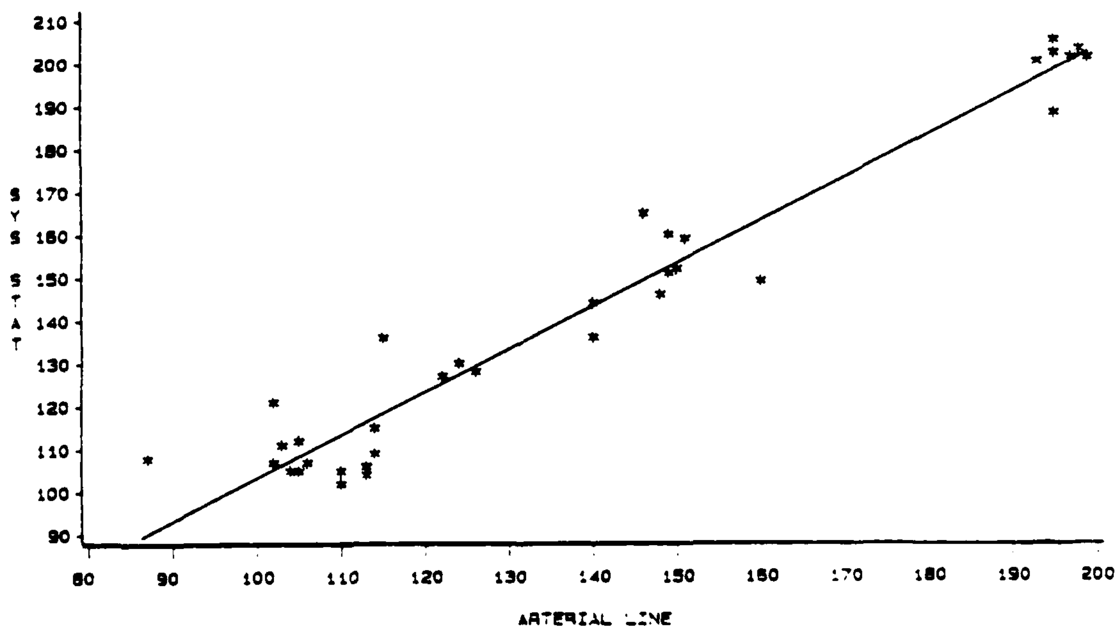


Figure 17. Scatterplot: sys stat versus arterial catheter for patient 5 (All values in mmHg).

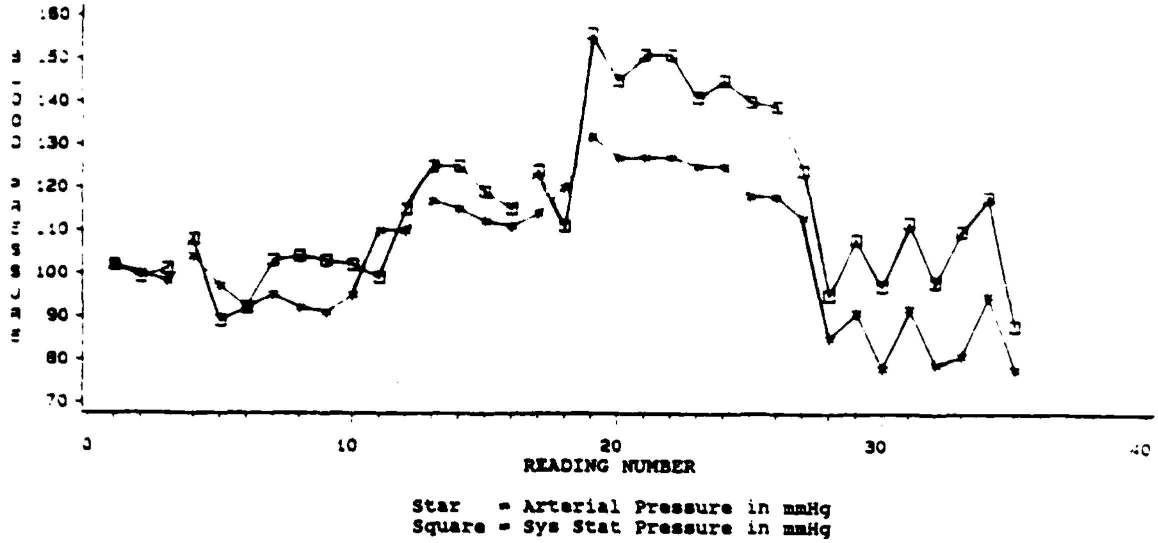


Figure 18. Descriptive statistics: sys stat versus arterial catheter for patient 6.

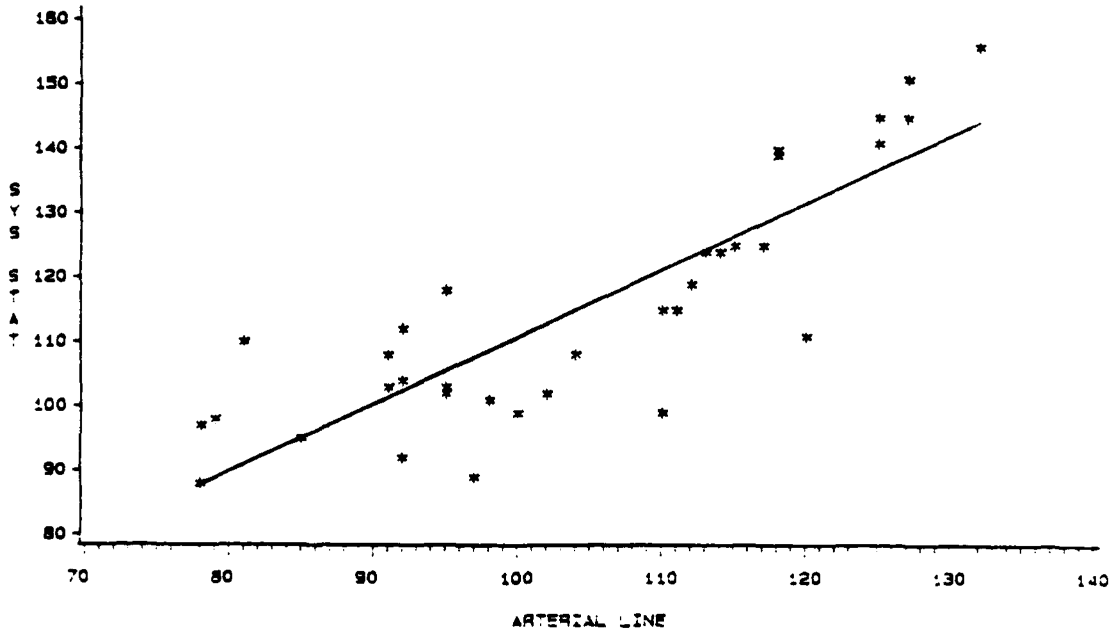


Figure 19. Scatterplot: sys stat versus arterial catheter for patient 6.

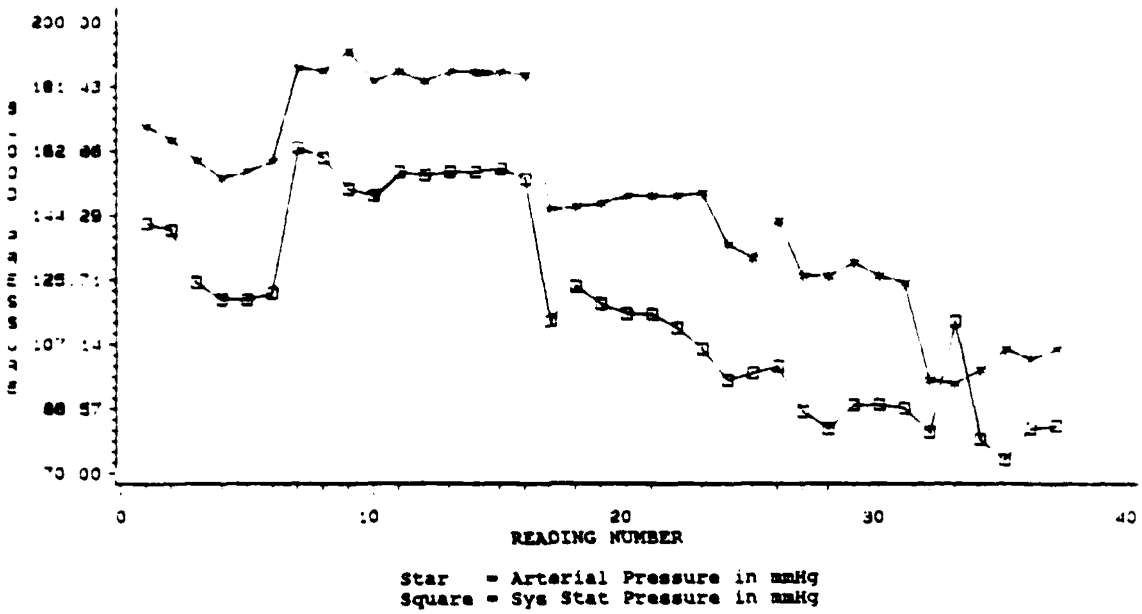


Figure 20. Descriptive statistics: sys stat versus arterial catheter for patient 7.

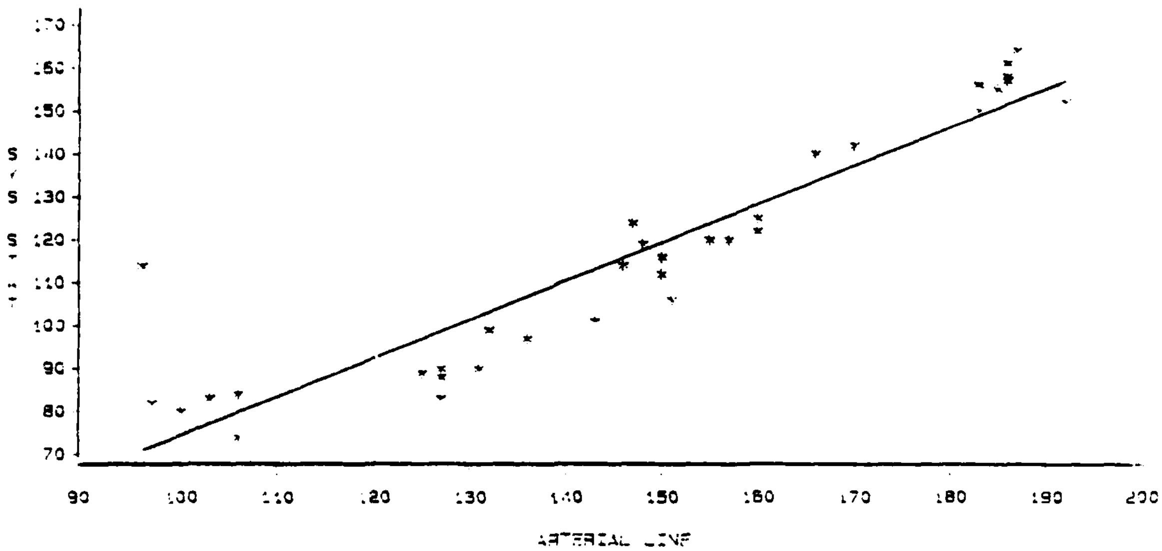


Figure 21. Scatterplot: sys stat versus arterial catheter for patient 7 (All values in mmHg).

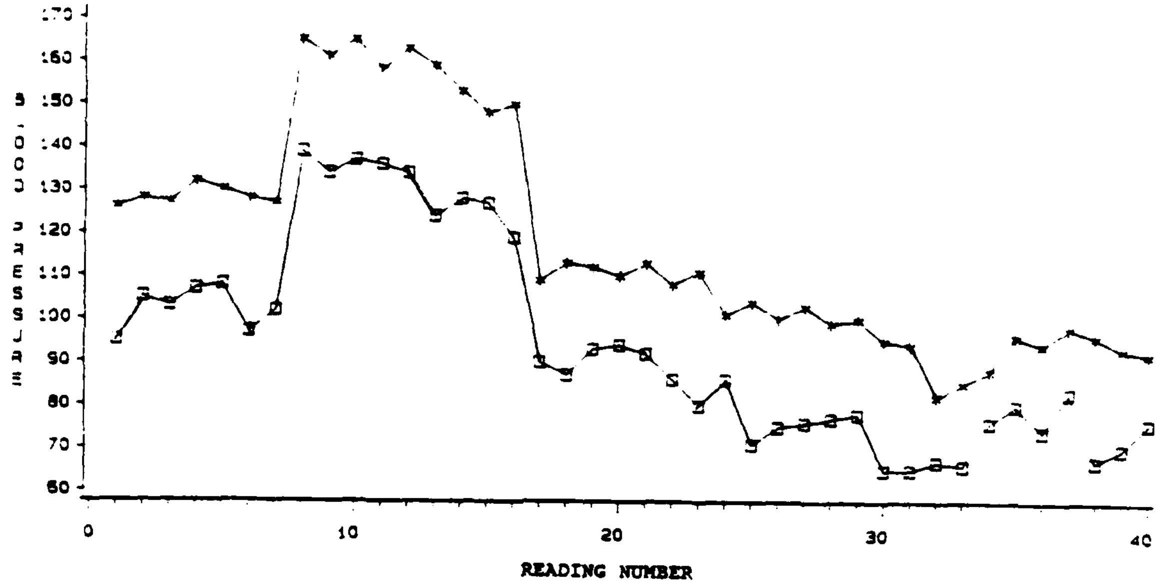


Figure 22. Descriptive statistics: sys stat versus arterial catheter for patient 8.

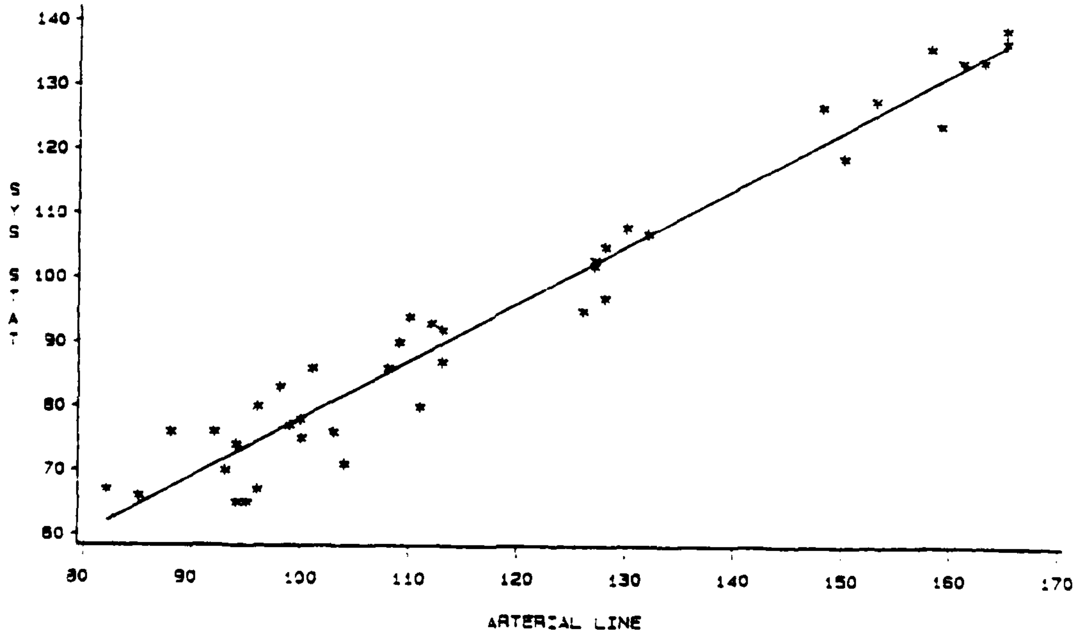


Figure 23. Scatterplot: sys stat versus arterial catheter for patient 8 (All values in mmHg).

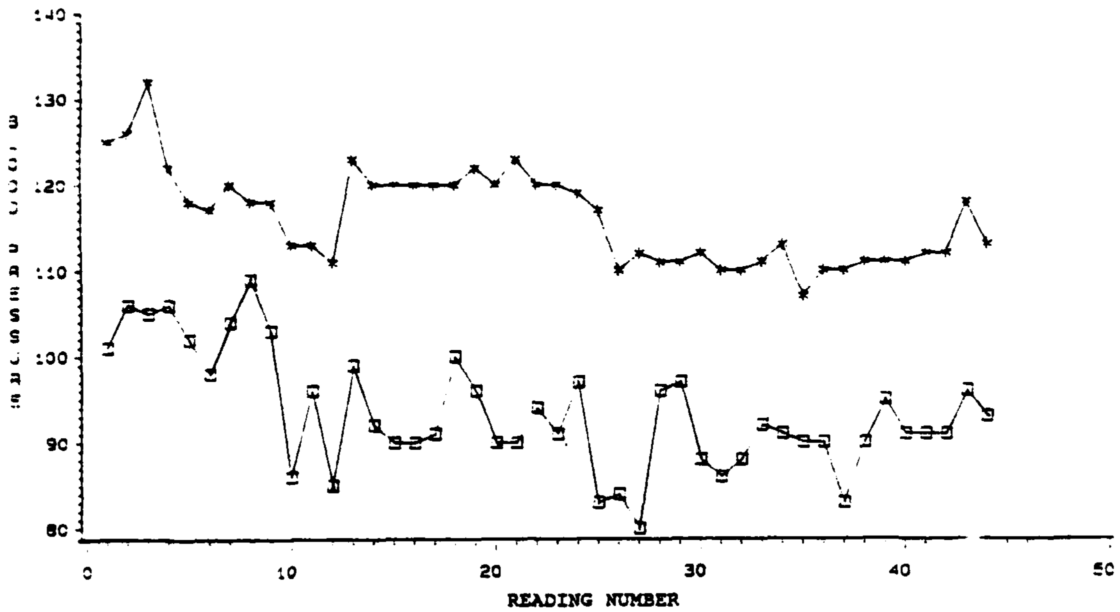


Figure 24. Descriptive statistics: sys stat versus arterial catheter for patient 9.

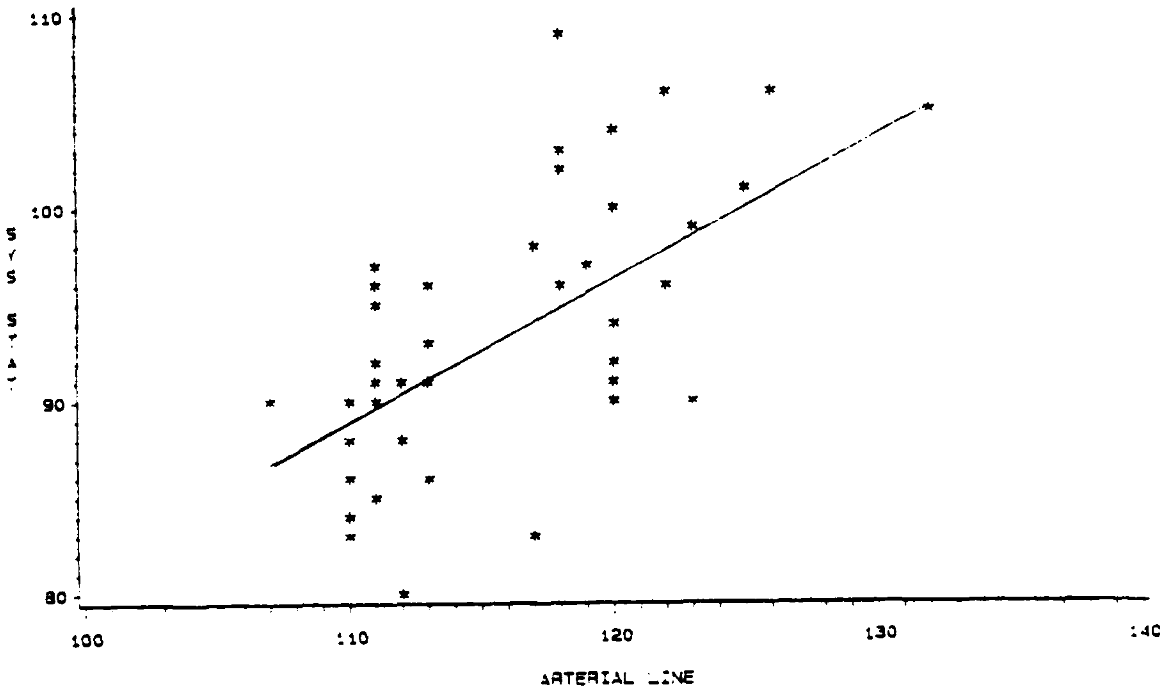


Figure 25. Scatterplot: sys stat versus arterial catheter for patient 9 (All values in mmHg).

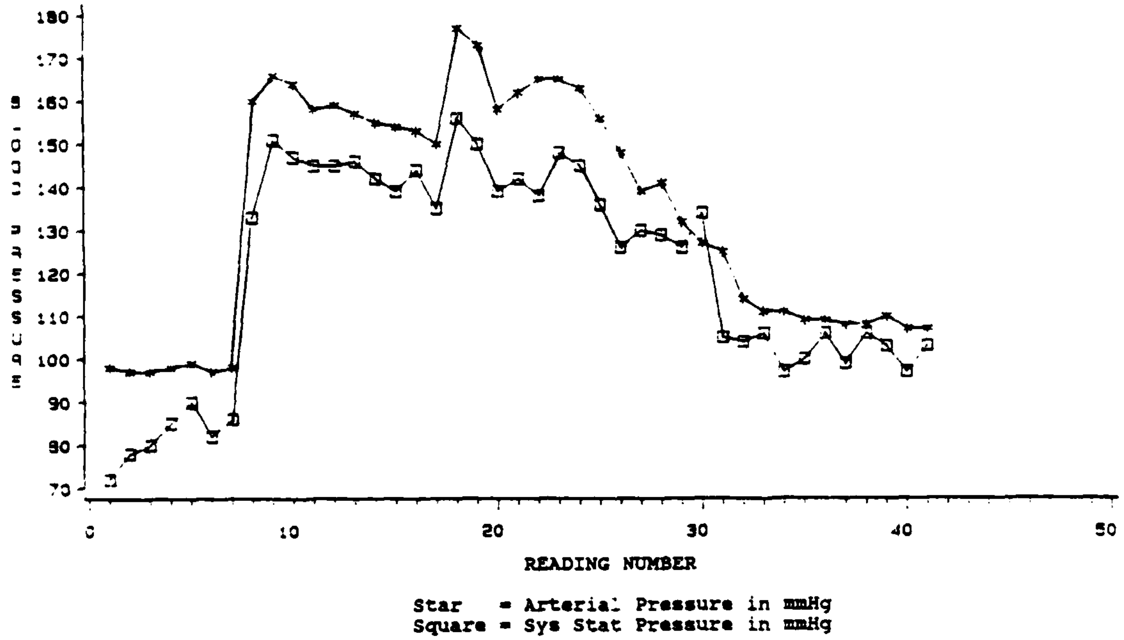


Figure 26. Descriptive statistics: sys stat versus arterial catheter for patient 10.

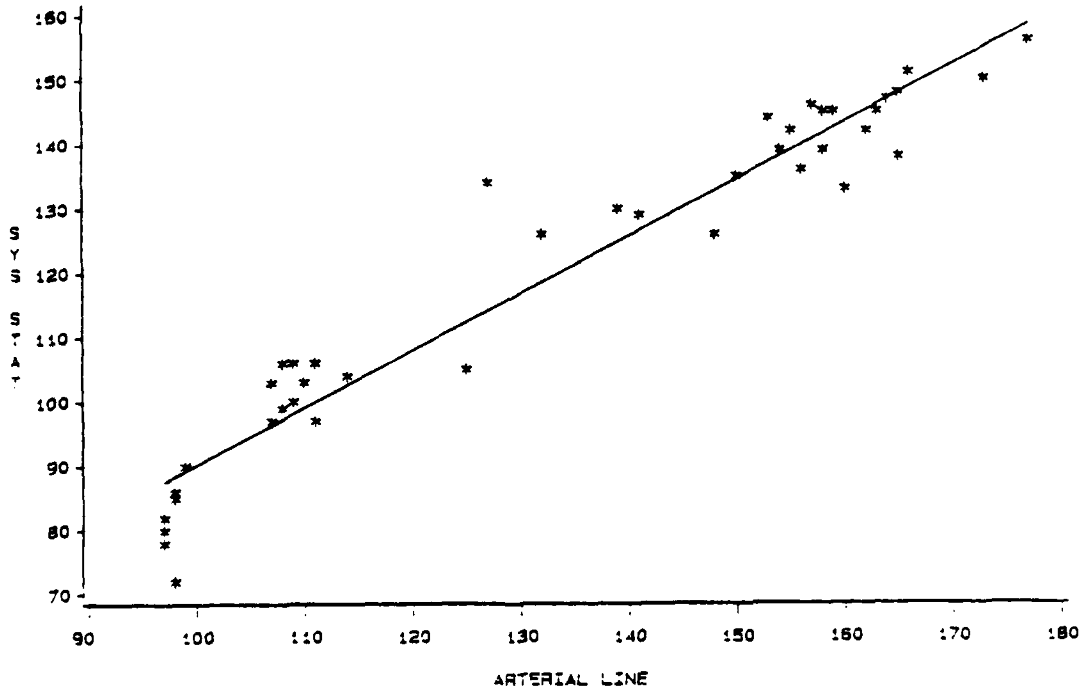


Figure 27. Scatterplot: sys stat versus arterial catheter for patient 10 (All values in mmHg).

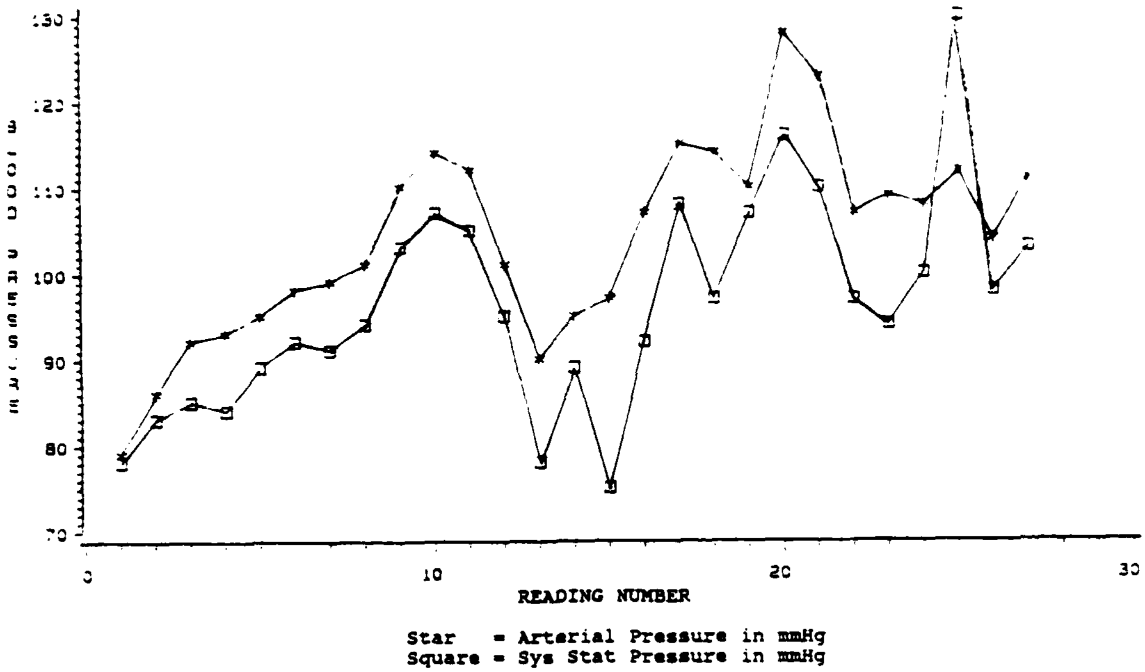


Figure 28. Descriptive statistics: sys stat versus arterial catheter for patient 11.

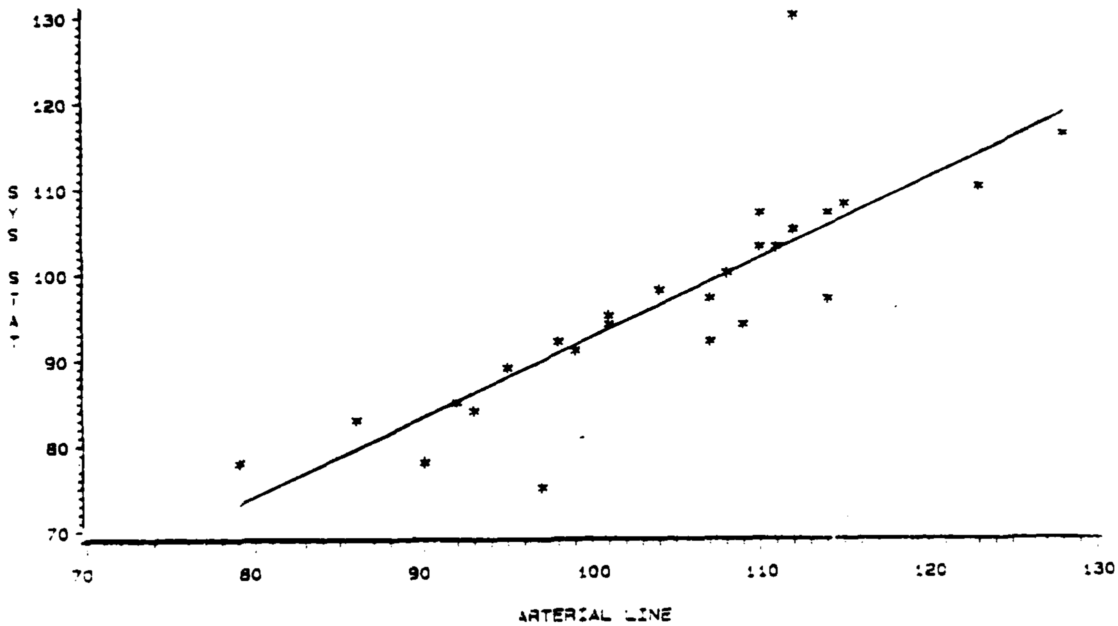


Figure 29. Scatterplot: sys stat versus arterial catheter for patient 11 (All values in mmHg).

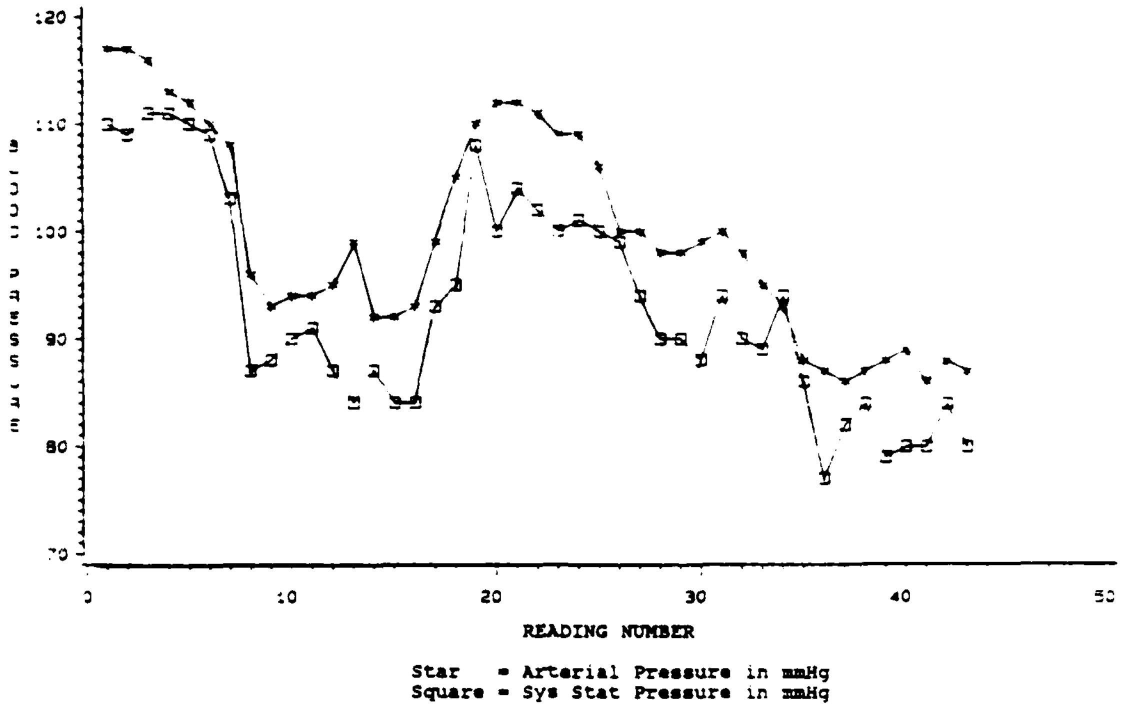


Figure 30. Descriptive statistics: sys stat versus arterial catheter for patient 12.

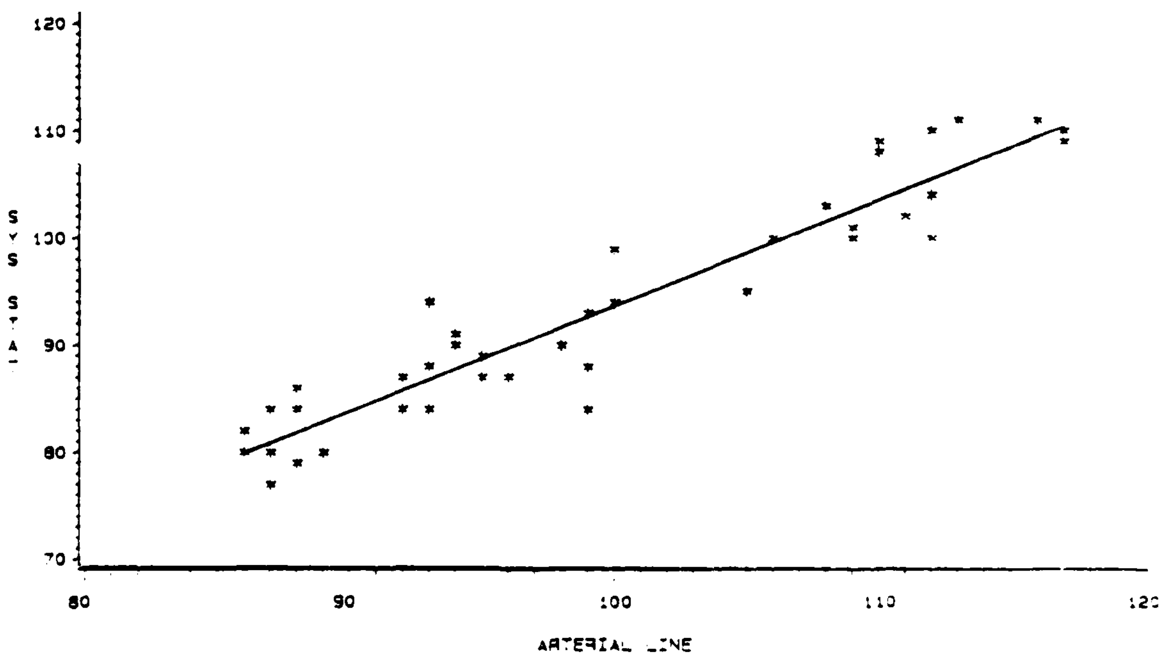


Figure 31. Scatterplot: sys stat versus arterial catheter for patient 12 (All values in mmHg).

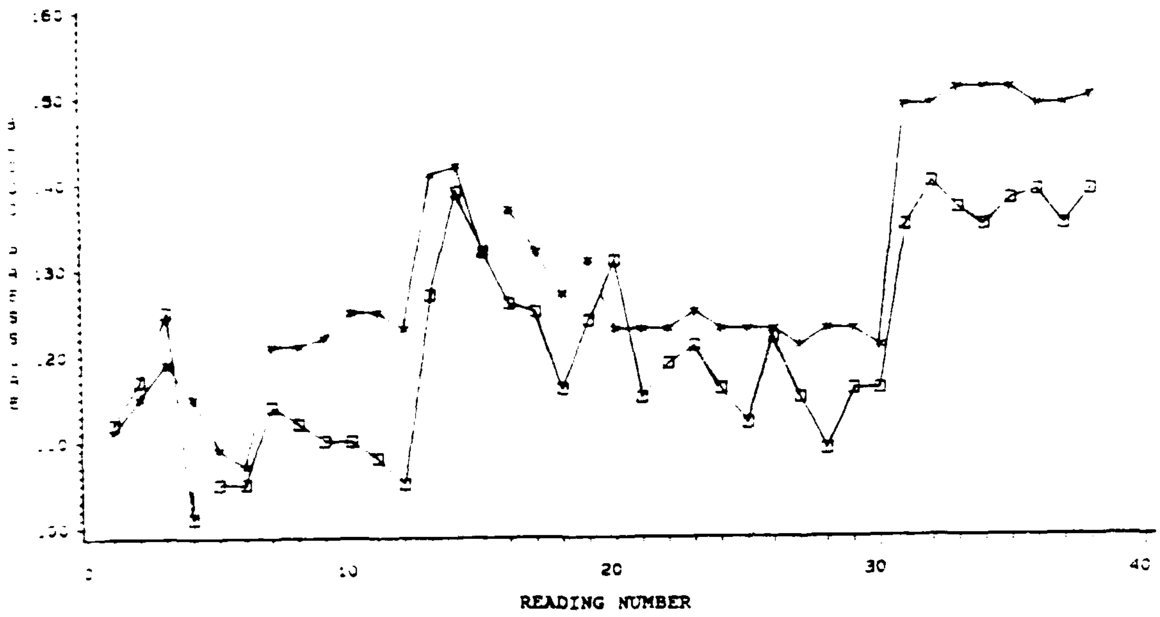


Figure 32. Descriptive statistics: sys stat versus arterial catheter for patient 13.

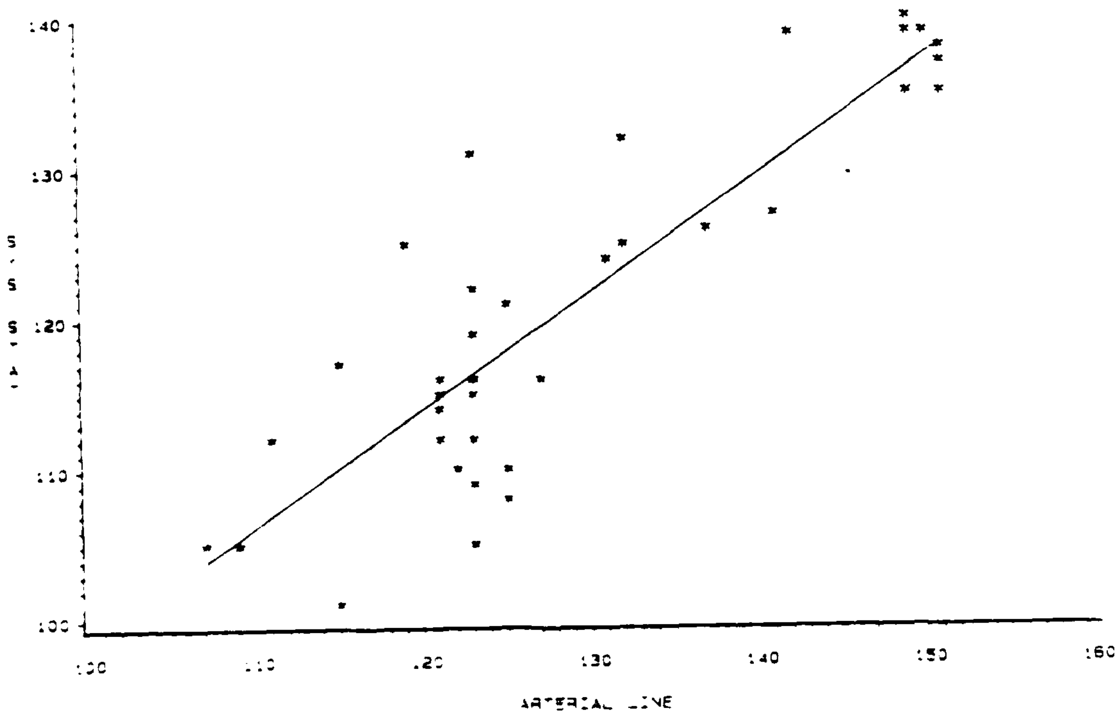


Figure 33. Scatterplot: sys stat versus arterial catheter for patient 13 (All values in mmHg).

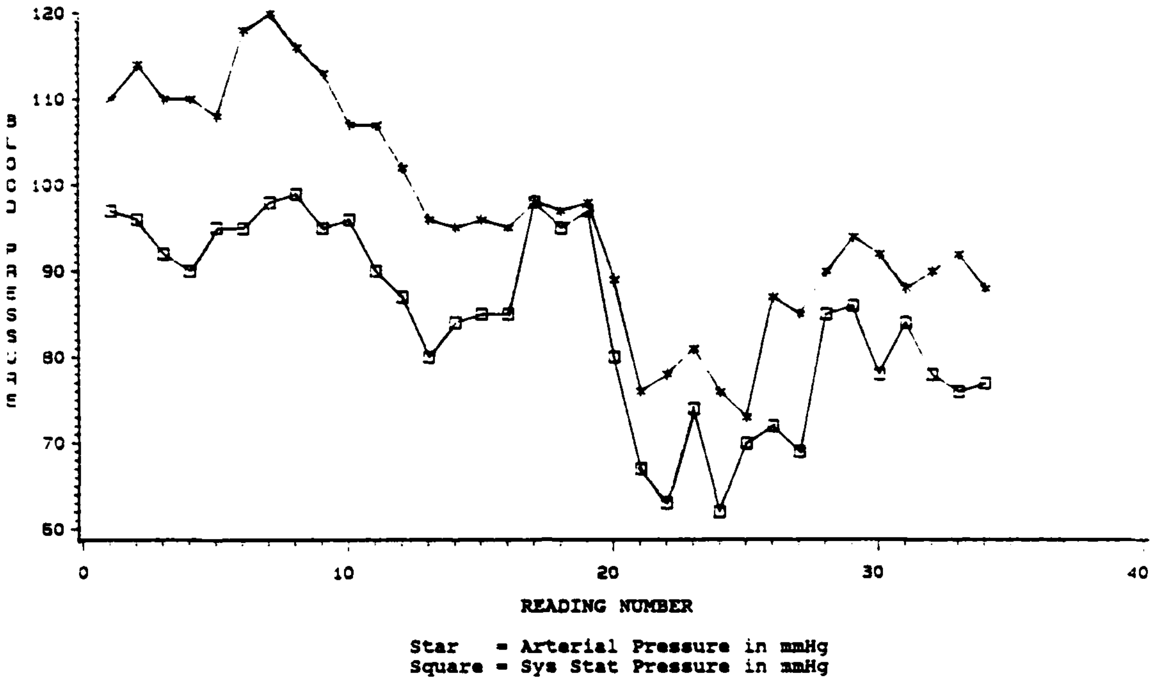


Figure 34. Descriptive statistics: sys stat versus arterial catheter for patient 14.

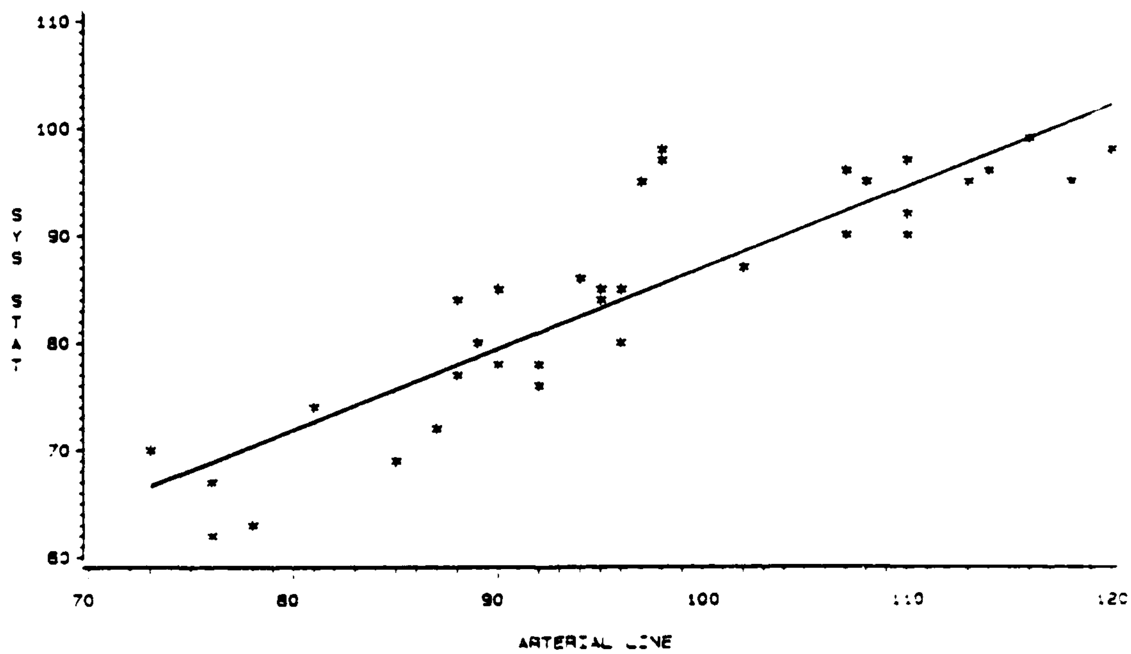


Figure 35. Scatterplot: sys stat versus arterial catheter for patient 14 (All values in mmHg).

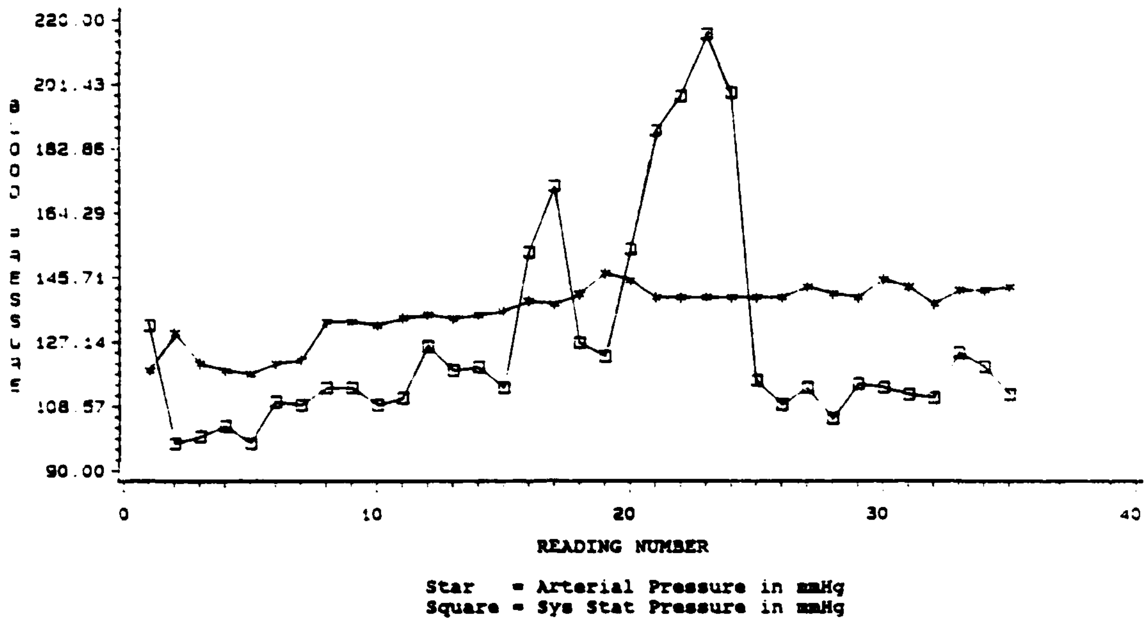


Figure 36. Descriptive statistics: sys stat versus arterial catheter for patient 15.

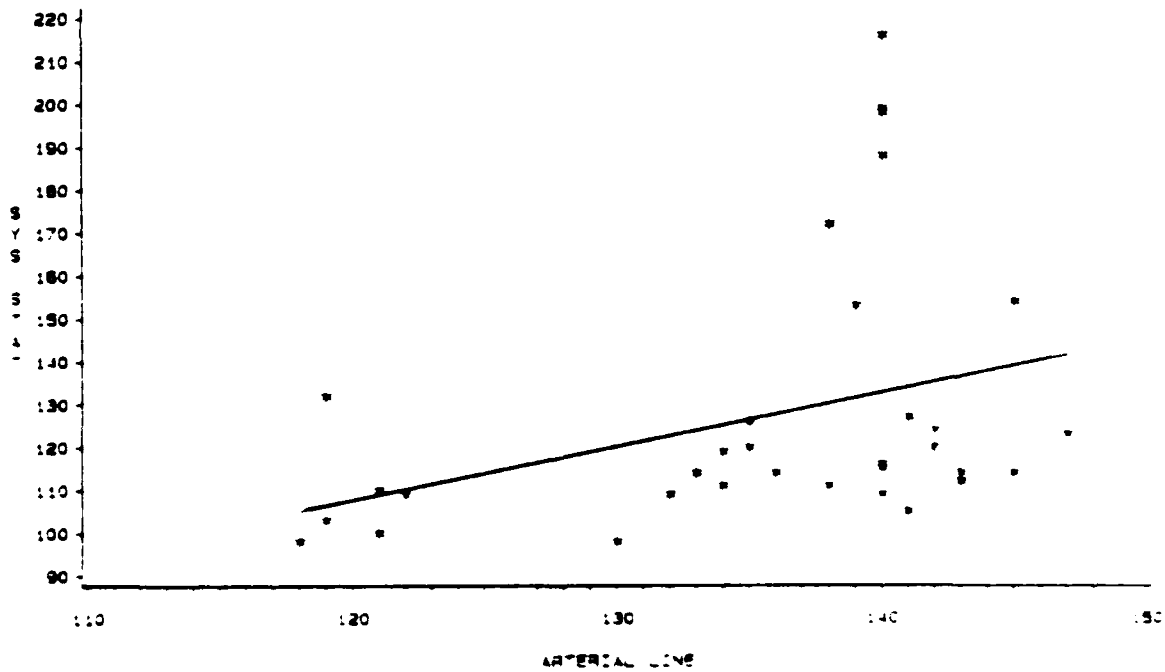


Figure 37. Scatterplot: sys stat versus arterial catheter for patient 15 (All values in mmHg).

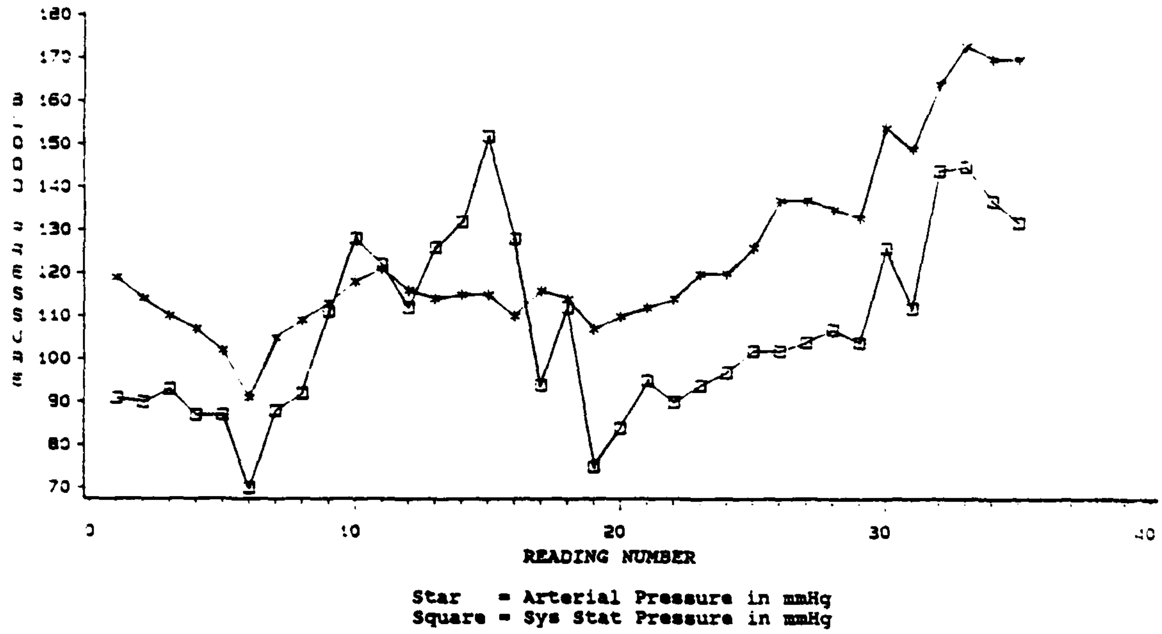


Figure 38. Descriptive statistics: sys stat versus arterial catheter for patient 16.

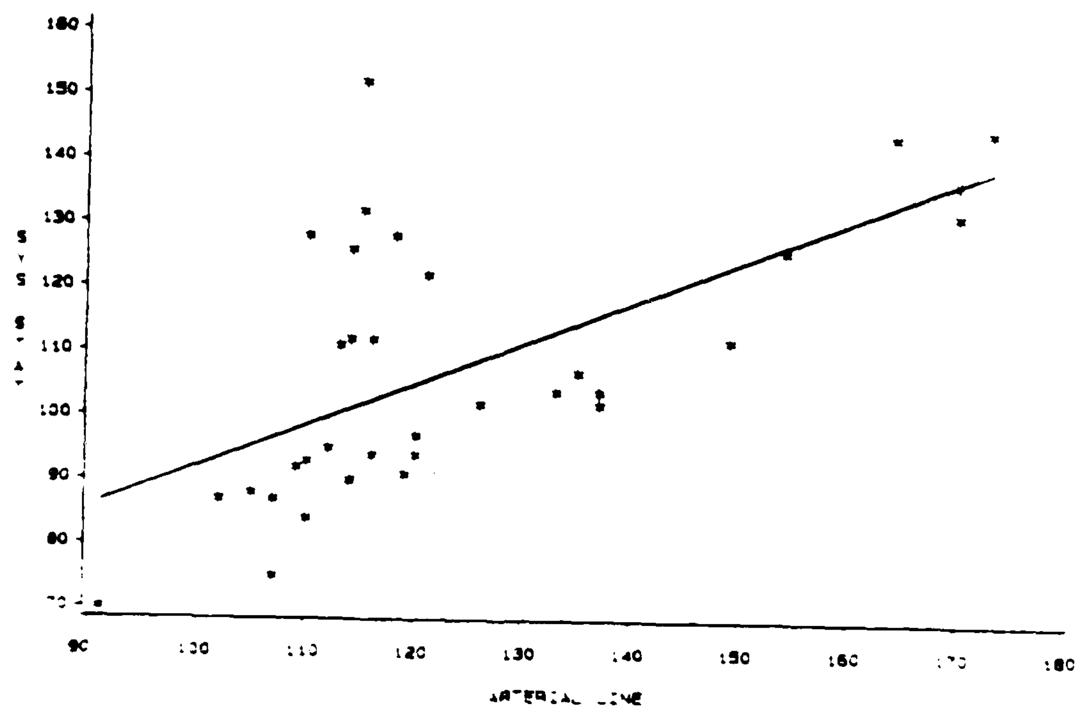


Figure 39. Scatterplot: sys stat versus arterial catheter for patient 16 (All values in mmHg).

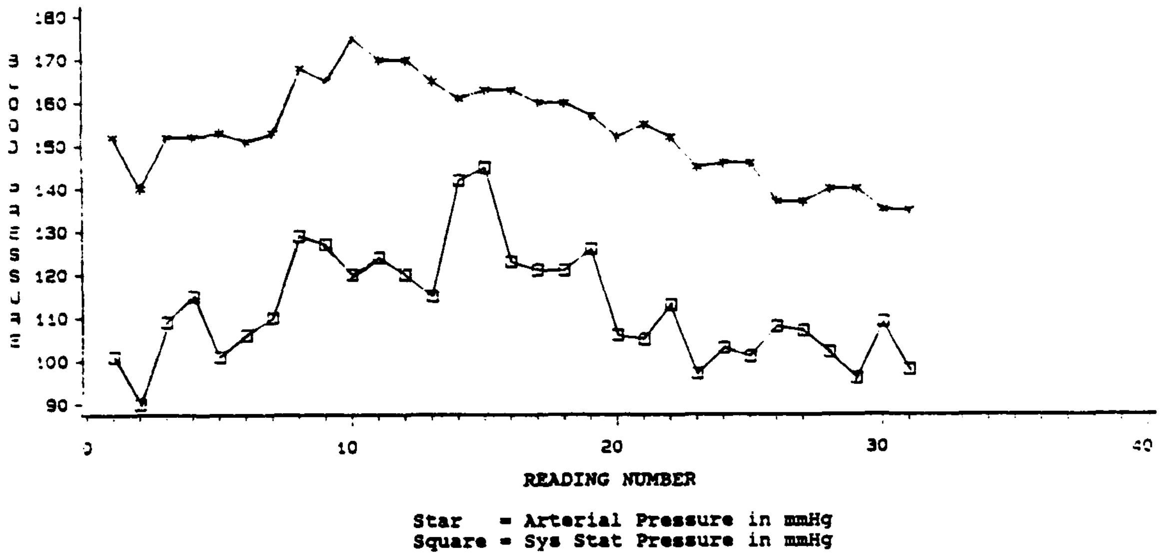


Figure 40. Descriptive statistics: sys stat versus arterial catheter for patient 17.

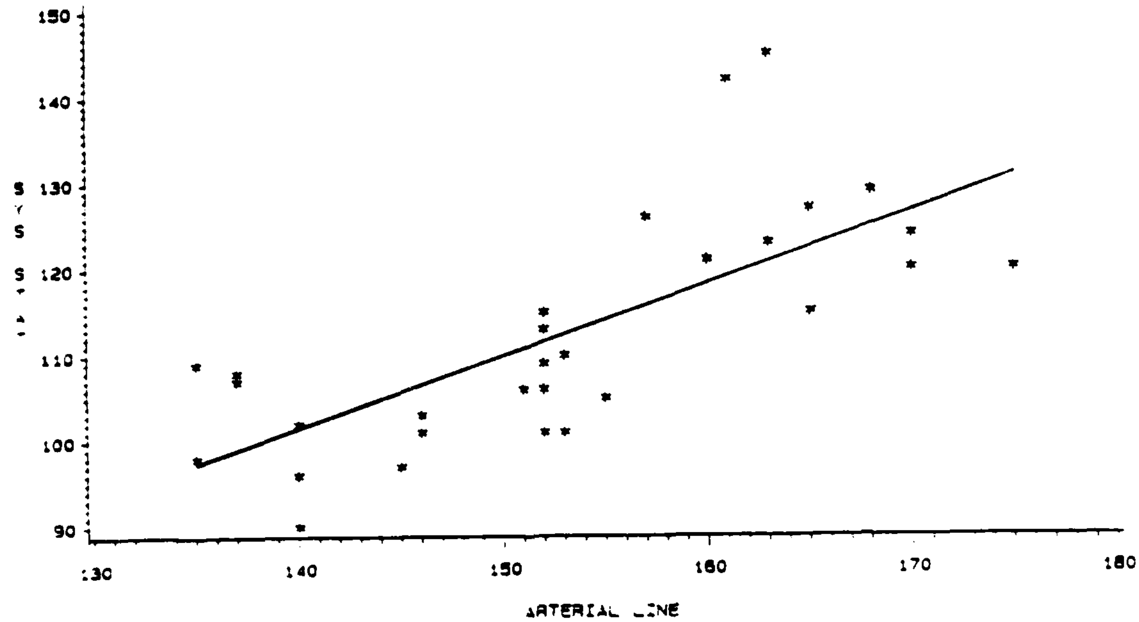


Figure 41. Scatterplot: sys stat versus arterial catheter for patient 17 (All values in mmHg).

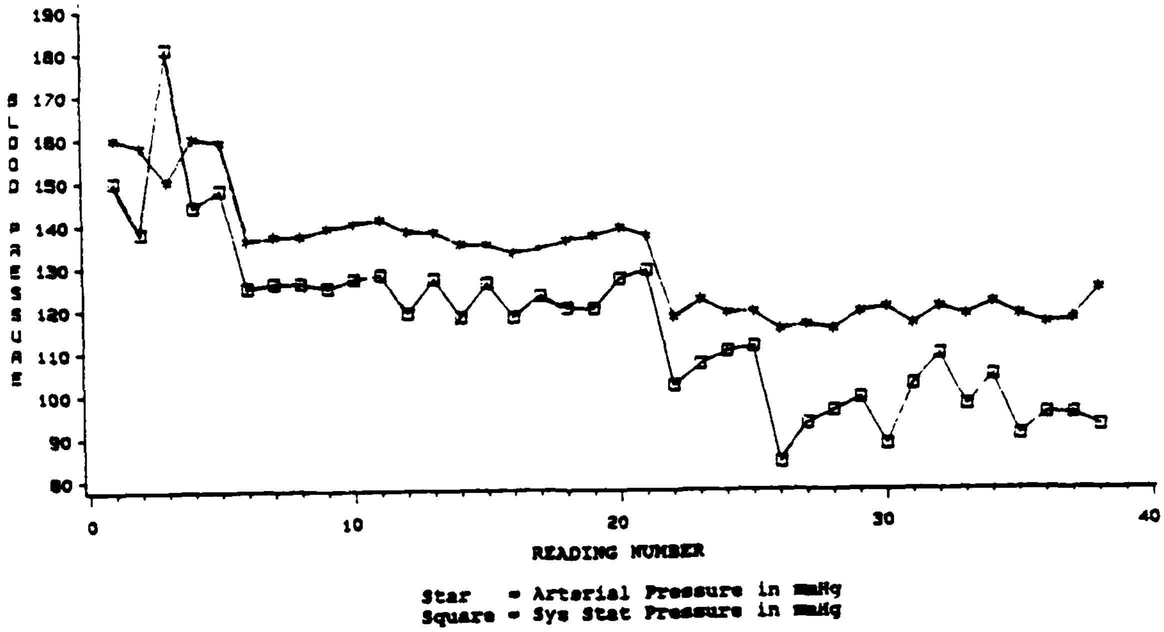


Figure 42. Descriptive statistics: sys stat versus arterial catheter for patient 18.

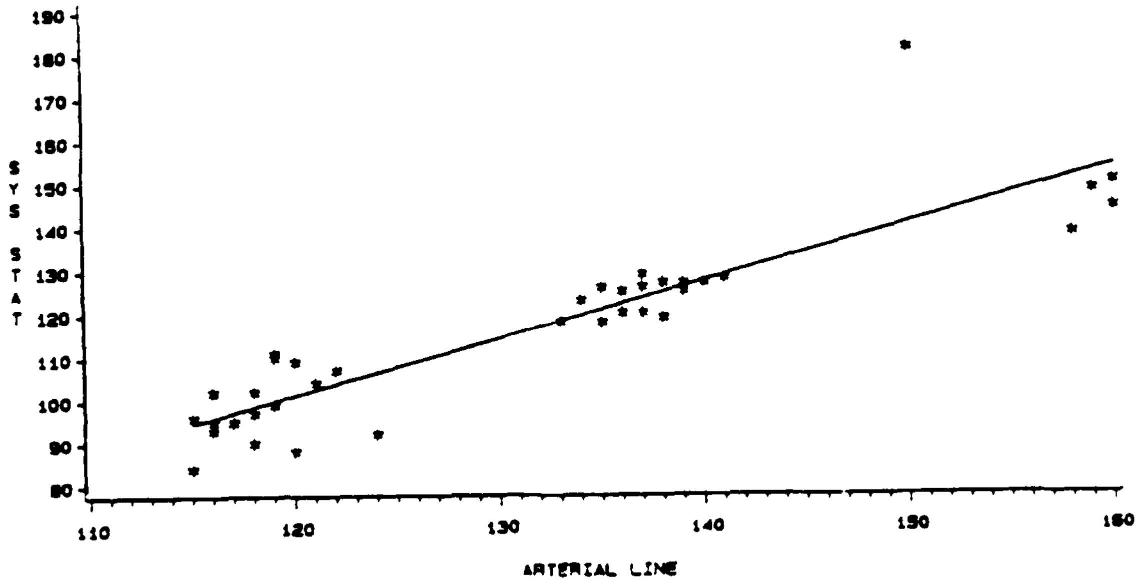


Figure 43. Scatterplot: sys stat versus arterial catheter for patient 18 (All values in mmHg).

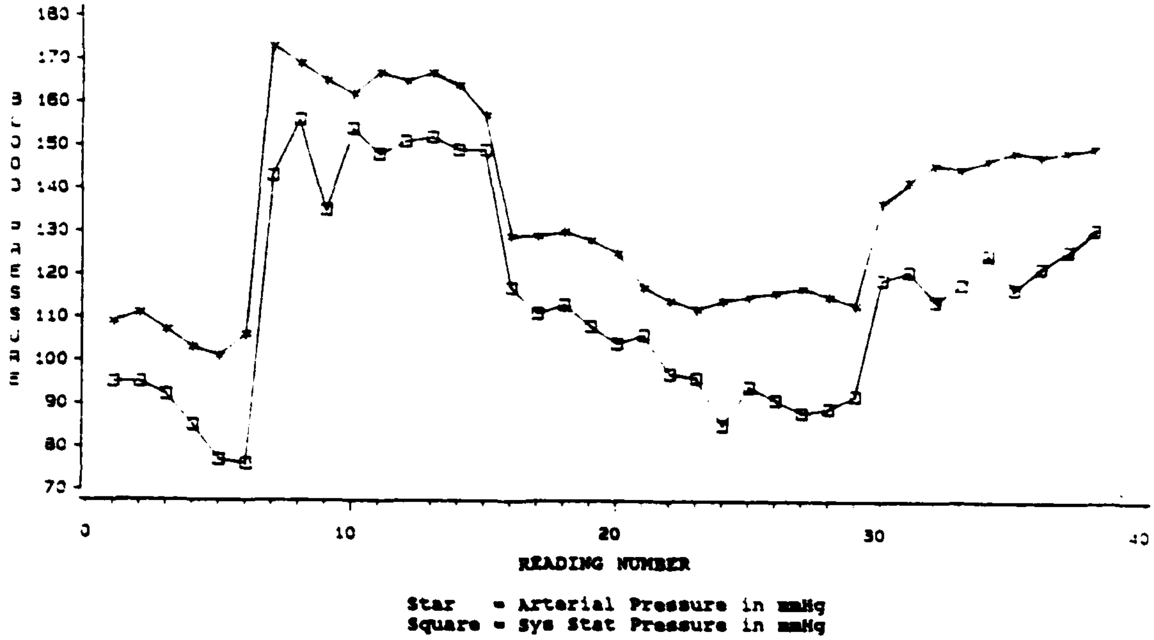


Figure 44. Descriptive statistics: sys stat versus arterial catheter for patient 19.

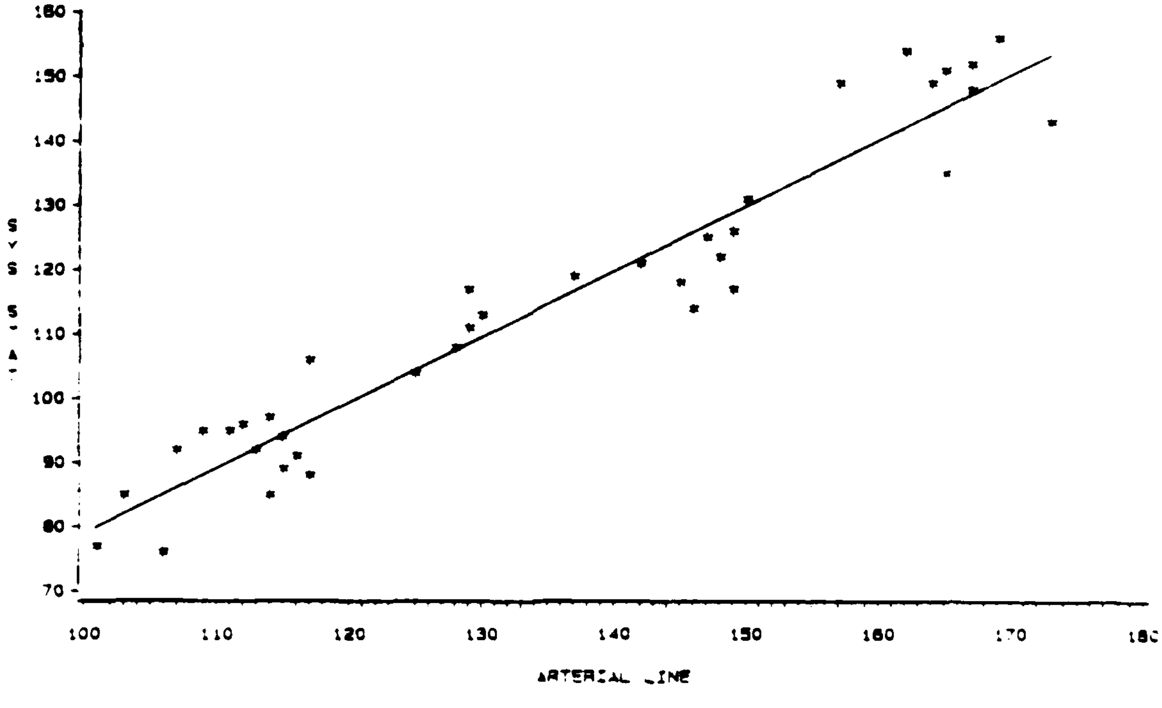


Figure 45. Scatterplot: sys stat versus arterial catheter for patient 19 (All values in mmHg).

Appendix B

Explanation to the Patient

The purpose of this study is to determine if there is a correlation between systolic blood pressure measured by an arterial catheter and systolic blood pressure measured by the return of blood flow to the finger.

The oscillatory method of blood pressure measurement is routinely used during anesthesia to monitor blood pressure. One of the drawbacks of this method is the length of time it can take to obtain a pressure measurement. To overcome this problem the use of a finger sensor to detect return of blood flow has been proposed as an more rapid alternative to determine systolic blood pressure.

As a planned part of your anesthesia an arterial catheter will be placed to either measure blood pressure or draw blood for laboratory analysis. The complications associated with an arterial catheter are bruising, infection and thrombus. In addition, the blood pressure cuff from the automatic blood pressure monitor will be placed on the upper portion of your other arm. The automatic blood pressure device on the upper arm is considered a routine practice in the operating room. There will also be a pulse detector placed on the middle finger on the same side as the blood pressure cuff.

The untoward effects of the automatic blood pressure monitor include damage to the ulnar or radial nerve and venous congestion. It has been shown this may occur if the cuff is inflated as frequently as once every minute. For this study the cuff will be inflated for one minute every three minutes for the first 10 to 20 minutes your surgery.

You may, at any time, revoke your consent and withdraw from the study without prejudice. You are encouraged to ask any questions you may have regarding this study now or at any time in the future.

If you agree to participate in this study, please sign your name below. Confidentiality will be maintained at all times. If at any time during the anesthesia, your safety is compromised, the study will be discontinued.

____

Signature Date

I was present during the explanation referred to above, as well as the volunteer's opportunity for questions, and hereby witness his/her signature.

____

Signature Date

Appendix B

Data Collection Form

Patient #

Ht sex

Wt age

Arm circumference
R L

Allen Test in second
R L

Pre-op BP in arms
R / L /

EKG tracing

Pre induction BP
Cuff sys
dias
mean
Pre induction Bp
Line sys
dias
mean

Pulse rate range

Stat sys	A-ln sys	Stat sy	A-ln sys

Appendix D

Raw Data

Patient Number	Set Number	First or Last	Sys Stat	Arterial Catheter
1	1	f	114	142
1	1	n	94	137
1	1	n	85	138
1	1	n	84	136
1	1	n	89	135
1	1	n	94	146
1	1	n	90	140
1	1	l	86	130
1	2	f	109	122
1	2	n	89	123
1	2	n	79	122
1	2	n	89	122
1	2	n	86	123
1	2	n	85	125
1	2	n	92	123
1	2	n	92	125
1	2	l	94	126
1	3	f	102	111
1	3	n	102	113
1	3	n	77	116
1	3	n	76	116
1	3	n	80	116
1	3	l	89	117
1	4	f	117	126
1	4	n	115	129
1	4	n	94	129
1	4	n	96	130
1	4	n	107	130
1	4	n	88	128
1	4	n	95	132
1	4	n	93	130
1	4	l	96	131
1	5	f	124	130
1	5	n	121	129
1	5	n	93	134
1	5	n	98	137
1	5	n	91	136
1	5	n	91	136
1	5	n	100	138
1	5	n	92	137
1	5	l	92	140
2	1	f	112	128
2	1	n	104	124
2	1	n	124	130

2	1	n	130	145
2	1	n	137	141
2	1	n	129	137
2	1	n	117	139
2	2	f	126	114
2	2	n	126	118
2	2	n	135	127
2	2	n	144	115
2	2	n	160	112
2	2	n	180	137
2	2	l	240	115
2	3	f	161	168
2	3	n	172	177
2	3	n	172	179
2	3	n	170	173
2	3	n	171	172
2	3	n	166	165
2	3	n	163	167
2	3	l	163	163
2	4	f	127	134
2	4	n	124	129
2	4	n	129	123
2	4	n	117	122
2	4	n	108	121
2	4	n	109	116
2	4	l	103	114
4	1	f	152	144
4	1	n	105	121
4	1	n	88	116
4	1	n	111	114
4	1	l	126	112
4	2	f	118	133
4	2	n	126	135
4	2	n	135	134
4	2	n	139	134
4	2	l	144	127
4	3	f	66	98
4	3	n	92	97
4	3	n	97	102
4	3	n	95	110
4	3	n	97	112
4	3	l	103	115
4	4	f	94	110
4	4	n	69	99
4	4	n	87	103
4	4	n	93	103
4	4	n	78	100
4	4	n	81	101
4	4	n	72	99
4	4	l	89	96
4	5	f	98	102
4	5	n	103	100

4	5	n	89	100
4	5	n	90	97
4	5	n	87	106
4	5	l	86	99
5	1	f	107	106
5	1	n	104	113
5	1	n	106	113
5	1	n	106	113
5	1	n	105	110
5	1	n	115	114
5	1	l	102	110
5	2	f	121	102
5	2	n	105	104
5	2	n	127	122
5	2	n	128	126
5	2	n	109	114
5	2	n	136	115
5	2	n	130	124
5	2	n	136	140
5	2	l	144	140
5	3	f	108	87
5	3	n	114	*
5	3	n	106	*
5	3	n	112	105
5	3	n	107	102
5	3	n	111	103
5	3	l	105	105
5	4	f	149	160
5	4	n	188	195
5	4	n	203	198
5	4	n	201	197
5	4	n	200	193
5	4	n	202	195
5	4	n	205	195
5	4	n	202	195
5	4	n	201	199
5	4	l	201	199
5	5	f	165	146
5	5	n	151	149
5	5	n	160	149
5	5	n	152	150
5	5	n	159	151
5	5	l	146	148
6	1	f	102	102
6	1	n	99	100
6	1	n	101	98
6	1	n	108	104
6	1	n	89	97
6	1	l	92	92
6	2	f	103	95
6	2	n	104	92
6	2	n	103	91

6	2	n	102	95
6	2	n	99	110
6	2	l	115	110
6	3	f	125	117
6	3	n	125	115
6	3	n	119	112
6	3	n	115	111
6	3	n	124	114
6	3	l	111	120
6	4	f	156	132
6	4	n	145	127
6	4	n	151	127
6	4	n	151	127
6	4	n	141	125
6	4	n	145	125
6	4	n	140	118
6	4	n	139	118
6	4	l	124	113
6	5	f	95	85
6	5	n	108	91
6	5	n	97	78
6	5	n	112	92
6	5	n	98	79
6	5	n	110	81
6	5	n	118	95
6	5	l	88	78
7	1	f	142	170
7	1	n	140	166
7	1	n	125	160
7	1	n	120	155
7	1	n	120	157
7	1	l	122	160
7	2	f	164	187
7	2	n	161	186
7	2	n	152	192
7	2	n	150	183
7	2	n	157	186
7	2	n	156	183
7	2	n	157	186
7	2	n	157	186
7	2	n	158	186
7	2	l	155	185
7	3	f	114	146
7	3	n	124	147
7	3	n	119	148
7	3	n	116	150
7	3	n	116	150
7	3	n	112	150
7	3	l	106	151
7	4	f	97	136
7	4	n	99	132
7	4	n	101	143

7	4	n	88	127
7	4	n	83	127
7	4	n	90	131
7	4	n	90	127
7	4	l	89	125
7	5	f	82	97
7	5	n	114	96
7	5	n	80	100
7	5	n	74	106
7	5	n	83	103
7	5	l	84	106
8	1	f	95	126
8	1	n	105	128
8	1	n	103	127
8	1	n	107	132
8	1	n	108	130
8	1	n	97	128
8	1	l	102	127
8	2	f	139	165
8	2	n	134	161
8	2	n	137	165
8	2	n	136	158
8	2	n	134	163
8	2	n	124	159
8	2	n	128	153
8	2	n	127	148
8	2	l	119	150
8	3	f	90	109
8	3	n	87	113
8	3	n	93	112
8	3	n	94	110
8	3	n	92	113
8	3	n	86	108
8	3	l	80	111
8	4	f	86	101
8	4	n	71	104
8	4	n	75	100
8	4	n	76	103
8	4	n	77	99
8	4	n	78	100
8	4	n	65	95
8	4	l	65	94
8	5	f	67	82
8	5	n	66	85
8	5	n	76	88
8	5	n	80	96
8	5	n	74	94
8	5	n	83	98
8	5	n	67	96
8	5	n	70	93
8	5	l	76	92
9	1	f	101	125

9	1	n	106	126
9	1	n	105	132
9	1	n	106	122
9	1	n	102	118
9	1	n	98	117
9	1	n	104	120
9	1	l	109	118
9	2	f	103	118
9	2	n	86	113
9	2	n	96	113
9	2	n	85	111
9	2	n	99	123
9	2	n	92	120
9	2	n	90	120
9	2	n	90	120
9	2	l	91	120
9	3	f	100	120
9	3	n	96	122
9	3	n	90	120
9	3	n	90	123
9	3	n	94	120
9	3	n	91	120
9	3	n	97	119
9	3	n	83	117
9	3	l	84	110
9	4	f	80	112
9	4	n	96	111
9	4	n	97	111
9	4	n	88	112
9	4	n	86	110
9	4	n	88	110
9	4	n	92	111
9	4	n	91	113
9	4	l	90	107
9	5	f	90	110
9	5	n	83	110
9	5	n	90	111
9	5	n	95	111
9	5	n	91	111
9	5	n	91	112
9	5	n	91	112
9	5	n	96	118
9	5	l	93	113
10	1	f	72	98
10	1	n	78	97
10	1	n	80	97
10	1	n	85	98
10	1	n	90	99
10	1	n	82	97
10	1	l	86	98
10	2	f	133	160
10	2	n	151	166

10	2	n	147	164
10	2	n	145	158
10	2	n	145	159
10	2	n	146	157
10	2	n	142	155
10	2	n	139	154
10	2	n	144	153
10	2	l	135	150
10	3	f	156	177
10	3	n	150	173
10	3	n	139	158
10	3	n	142	162
10	3	n	138	165
10	3	n	148	165
10	3	n	145	163
10	3	n	136	156
10	3	l	126	148
10	4	f	130	139
10	4	n	129	141
10	4	n	126	132
10	4	n	134	127
10	4	l	105	125
10	5	f	104	114
10	5	n	106	111
10	5	n	97	111
10	5	n	100	109
10	5	n	106	109
10	5	n	99	108
10	5	n	106	108
10	5	n	103	110
10	5	n	97	107
10	5	l	103	107
11	1	f	78	79
11	1	n	83	86
11	1	n	85	92
11	1	n	84	93
11	1	n	89	95
11	1	n	92	98
11	1	n	91	99
11	1	n	94	101
11	1	n	103	110
11	1	l	107	114
11	2	f	105	112
11	2	n	95	101
11	2	n	78	90
11	2	n	89	95
11	2	n	75	97
11	2	n	92	107
11	2	n	108	115
11	2	n	97	114
11	2	l	107	110
11	3	f	116	128

11	3	n	110	123
11	3	n	97	107
11	3	n	94	109
11	3	n	100	108
11	3	n	130	112
11	3	n	98	104
11	3	l	103	111
12	1	f	110	117
12	1	n	109	117
12	1	n	111	116
12	1	n	111	113
12	1	n	110	112
12	1	n	109	110
12	1	l	103	108
12	2	f	87	96
12	2	n	88	93
12	2	n	90	94
12	2	n	91	94
12	2	n	87	95
12	2	n	84	99
12	2	n	87	92
12	2	n	84	92
12	2	l	84	93
12	3	f	93	99
12	3	n	95	105
12	3	n	108	110
12	3	n	100	112
12	3	n	104	112
12	3	n	102	111
12	3	n	100	109
12	3	n	101	109
12	3	l	100	106
12	4	f	99	100
12	4	n	94	100
12	4	n	90	98
12	4	n	90	98
12	4	n	88	99
12	4	n	94	100
12	4	n	90	98
12	4	n	89	95
12	4	l	94	93
12	5	f	86	88
12	5	n	77	87
12	5	n	82	86
12	5	n	84	87
12	5	n	79	88
12	5	n	80	89
12	5	n	80	86
12	5	n	84	88
12	5	l	80	87
13	1	f	112	111
13	1	n	117	115

13	1	n	125	119
13	1	n	101	115
13	1	n	105	109
13	1	l	105	107
13	2	f	114	121
13	2	n	112	121
13	2	n	110	122
13	2	n	110	125
13	2	n	108	125
13	2	l	105	123
13	3	f	127	141
13	3	n	139	142
13	3	n	132	132
13	3	n	126	137
13	3	n	125	132
13	3	n	116	127
13	3	n	124	131
13	3	n	131	123
13	3	l	115	123
13	4	f	119	123
13	4	n	121	125
13	4	n	116	123
13	4	n	112	123
13	4	n	122	123
13	4	n	115	121
13	4	n	109	123
13	4	n	116	123
13	4	l	116	121
13	5	f	135	149
13	5	n	140	149
13	5	n	137	151
13	5	n	135	151
13	5	n	138	151
13	5	n	139	149
13	5	n	135	149
13	5	l	139	150
14	1	f	97	110
14	1	n	96	114
14	1	n	92	110
14	1	n	90	110
14	1	n	95	108
14	1	n	95	118
14	1	l	98	120
14	2	f	99	116
14	2	n	95	113
14	2	n	96	107
14	2	n	90	107
14	2	n	87	102
14	2	n	80	96
14	2	n	84	95
14	2	l	85	96
14	3	f	85	95

14	3	n	98	98
14	3	n	95	97
14	3	n	97	98
14	3	l	80	89
14	4	f	67	76
14	4	n	63	78
14	4	n	74	81
14	4	n	62	76
14	4	l	70	73
14	5	f	72	87
14	5	n	69	85
14	5	n	85	90
14	5	n	86	94
14	5	n	78	92
14	5	n	84	88
14	5	n	78	90
14	5	n	76	92
14	5	l	77	88
15	1	f	132	119
15	1	n	98	130
15	1	n	100	121
15	1	n	103	119
15	1	n	98	118
15	1	n	110	121
15	1	l	109	122
15	2	f	114	133
15	2	n	114	133
15	2	n	109	132
15	2	n	111	134
15	2	n	126	135
15	2	n	119	134
15	2	n	120	135
15	2	l	114	136
15	3	f	153	139
15	3	n	172	138
15	3	n	127	141
15	3	n	123	147
15	3	l	154	145
15	4	f	188	140
15	4	n	198	140
15	4	n	216	140
15	4	n	199	140
15	4	l	116	140
15	5	f	109	140
15	5	n	114	143
15	5	n	105	141
15	5	n	115	140
15	5	n	114	145
15	5	n	112	143
15	5	n	111	138
15	5	n	124	142
15	5	n	120	142

15	5	l	112	143
16	1	f	91	119
16	1	n	90	114
16	1	n	93	110
16	1	n	87	107
16	1	n	87	102
16	1	l	70	91
16	2	f	88	105
16	2	n	92	109
16	2	n	111	113
16	2	n	128	118
16	2	n	122	121
16	2	n	112	116
16	2	n	126	114
16	2	n	132	115
16	2	n	152	115
16	2	l	128	110
16	3	f	94	116
16	3	n	112	114
16	3	n	75	107
16	3	l	84	110
16	4	f	95	112
16	4	n	90	114
16	4	n	94	120
16	4	n	97	120
16	4	n	102	126
16	4	n	102	137
16	4	n	104	137
16	4	n	107	135
16	4	l	104	133
16	5	f	126	154
16	5	n	112	149
16	5	n	144	164
16	5	n	145	173
16	5	n	197	170
16	5	l	132	170
17	1	f	95	109
17	1	n	95	111
17	1	n	92	107
17	1	n	85	103
17	1	n	77	101
17	1	l	76	106
17	2	f	143	173
17	2	n	156	169
17	2	n	135	165
17	2	n	154	162
17	2	n	148	167
17	2	n	151	165
17	2	n	152	167
17	2	n	149	164
17	2	l	149	157
17	3	f	117	129

17	3	n	111	129
17	3	n	113	130
17	3	n	108	128
17	3	n	104	125
17	3	l	106	117
17	4	f	97	114
17	4	n	96	112
17	4	n	85	114
17	4	n	94	115
17	4	n	91	116
17	4	n	88	117
17	4	n	89	115
17	4	l	92	113
17	5	f	119	137
17	5	n	121	142
17	5	n	114	146
17	5	n	118	145
17	5	n	125	147
17	5	n	117	149
17	5	n	122	148
17	5	n	126	149
17	5	l	131	150
18	1	f	101	152
18	1	n	90	140
18	1	n	109	152
18	1	n	115	152
18	1	n	101	153
18	1	n	106	151
18	1	l	110	153
18	2	f	129	168
18	2	n	127	165
18	2	n	120	175
18	2	n	124	170
18	2	n	120	179
18	2	l	115	165
18	3	f	142	161
18	3	n	145	163
18	3	n	123	163
18	3	n	121	160
18	3	n	121	160
18	3	l	126	157
18	4	f	106	152
18	4	n	105	155
18	4	n	113	152
18	4	n	97	145
18	4	n	103	146
18	4	l	101	146
18	5	f	108	137
18	5	n	107	137
18	5	n	102	140
18	5	n	96	140
18	5	n	109	135

18	5	l	98	135
19	1	f	150	160
19	1	n	138	158
19	1	n	181	150
19	1	n	144	160
19	1	l	148	159
19	2	f	125	136
19	2	n	126	137
19	2	n	126	137
19	2	n	125	139
19	2	n	127	140
19	2	n	128	141
19	2	n	119	138
19	2	l	127	138
19	3	f	118	135
19	3	n	126	135
19	3	n	118	133
19	3	n	123	134
19	3	n	120	136
19	3	n	120	137
19	3	n	127	139
19	3	l	129	137
19	4	f	102	118
19	4	n	107	122
19	4	n	110	119
19	4	n	111	119
19	4	n	84	115
19	4	n	93	116
19	4	n	96	115
19	4	n	99	119
19	4	l	88	120
19	5	f	102	116
19	5	n	109	120
19	5	n	97	118
19	5	n	104	121
19	5	n	90	118
19	5	n	95	116
19	5	n	95	117
19	5	l	92	124

Vita

Patricia J. McCaffrey was born on September 20, 1951, in Danville, Illinois, and is a citizen of the United States of America. She graduated from Governor Livingston Regional High School, Berkeley Heights, New Jersey, in 1970. She received an Associate of Applied Sciences Degree from Ocean County College in 1978 and a Bachelor of Science Degree in Nursing from the University of the State of New York in Albany in 1980. She has served on active duty with the United States Air Force since 1979 and has had assignments both within the continental United States and abroad.

END
3-87
DTIC